Hail Climatology Along the Northeastern Adriatic

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Abstract General awareness and overall interest regarding hailstorms and hail properties in Europe have increased significantly in the last several decades and have resulted in numerous local, national, and even Europe-wide studies on hail and hail properties. To contribute to this field, we determined the hail climatology in the northeastern (NE) Adriatic region and analyzed its spatial and temporal patterns and performed an objectively derived weather type analysis of ERA5 daily mean data and instability indices. We studied the NE Adriatic region due to its focus on agricultural activities and on quality wine production. Our results are based on approximately 60 years of high spatial resolution measurements collected from 27 stations across complex terrain. The results show (i) high levels of spatial variability, (ii) significant annual variations, and (iii) hail throughout the whole year that (iv) intensifies in summer months. Furthermore, redistribution of hail among seasons (in particular, from summer to spring) was detected. Most significant changes were visible in the June–October period, with a negative trend of −0.06 hail days/year, and the period from November to March exhibited a positive trend of 0.13 hail cases/year. We found that deep cyclonic systems in front of and above our domain were most responsible for hail generation, often supported by southwesterly winds. Additionally, the vast majority of observed hail events occurred in unstable and sheared environments.

1. Introduction

Over the past several decades in Europe, the general awareness and overall interest in hailstorms and hail properties have increased significantly. Even minor hail events can cause considerable damage to agricultural systems, and as hail increases in size, trees, greenhouses, vehicles, animals, and humans are more strongly affected (Půčík et al., 2019). Thus, any effort toward a better understanding of hail properties can help reduce damage and risks involved with hail.

Most hail properties, such as its annual and diurnal cycles, trends, and interannual and seasonal variations, can be identified through hail climatology. To date, hail climatology at local or national scales has been analyzed for the majority of European countries (Punge & Kunz, 2016). Data used in derivations of hail climatology include hailpad measurements (Manzato, 2011; Počakal et al., 2009; Sánchez et al., 2009), station measurements (e.g., Burcea et al., 2016; Ćurić & Janc, 2016; Kotinis-Zambakas, 1989; Vinet, 2001; Zhang et al., 2008), hail reports (e.g., Dessens, 1986; Tuovinen et al., 2009; Webb et al., 2001, 2009), radar estimates (Lukach et al., 2017; Nisi et al., 2016; Strzinar & Skok, 2018; Visser & van Heerden, 2000), satellite assessments (Punge et al., 2017), insurance damage data (Vinet, 2001), and global model outputs (Brooks et al., 2003; Hand & Cappelluti, 2011). Overall, the results show the presence of hail over much of Europe from the northern regions of Scandinavia (up to 67.5°N), where the hail season is shortest (during summer) (e.g., Tuovinen et al., 2009), to the Mediterranean region, where hail can occur throughout the year (e.g., Baldi et al., 2014; Berthet et al., 2011; Punge & Kunz, 2016). In addition, while continental regions are mainly affected by hail during the warmer parts of the year (e.g., April–September), coastal (maritime) regions along the Atlantic Ocean or Mediterranean show different hail frequency distributions. For coastal hail climatology, most cases occur during winter and spring but with relatively few hailstones (Punge & Kunz, 2016; Santos & Belo-Pereira, 2019). According to Punge et al. (2014), the areas with the most frequent hail events are positioned between 39°N and 50°N. Hail hotspots are found in highlands around the Alps, Medvednica, and the Velebit Range, as well as in the Dinarides in the Balkan Region, and Carpathians in the Pannonian Basin. Some reported hail frequencies have presented values of 0–2.4 hail days per year according to station measurements (Punge & Kunz, 2016).
while radar-based estimates have reported values of 0–2 hail days per year (Nisi et al., 2016; Strzinar & Skok, 2018). A recent publication by Punge et al. (2017) provides an estimation of hail frequencies from satellite-based overshooting tops (OTs) and ERA-Interim reanalyses of Europe. The authors reported 10 km × 10 km grided information for yearly hail frequency estimates that spanned 0–2 hail days (Punge et al., 2017; their Figure 6) and the spatial distributions corresponded well with previous studies.

While Croatia is situated in an area where strong impacts of hail are expected (e.g., Punge et al., 2014), the Adriatic Coast has never been analyzed in detail, and its national hail climatology has not yet been developed. Nevertheless, several papers have addressed the hail characteristics of the continental region of Croatia (Figure 1a, northwestern [NW] part of figure), which is an agricultural region that is well equipped with weather radar, meteorological stations, and hailpad networks. The hail properties and their characteristics in the continental part of Croatia are reported in Počakal and Štalec (2003) and Počakal et al. (2009, 2018). In these papers, the analyses focused on the warm season (i.e., May–September), which is connected with the hail suppression network and hailpad data. The main results show that the spatial and temporal characteristics of hail in the period from 1981 to 2006 show higher hail activity on the windward slopes of mountains. The hail frequencies in Croatia range from 0.1 to 2.4 hail days/season. The first 3 months of the hail season represent 84% of total hail cases, and hail is most active between 14 and 18 h local time. A positive significant trend for hail duration was also reported. In addition, the authors calculated that the average hypothetical length of hail streaks was approximately 1,890 m and that the average damaged area was approximately 0.7 km². According to analyses of lightning activity by MikušJurković et al. (2015), OT analyses by Punge et al. (2014) and lightning climatology results (Anderson & Klugmann, 2014; Mikuš et al., 2012; Poelman et al., 2016), the northeastern (NE) Adriatic (Figure 1b) appears to be a very active convective region and is similar to the southern part of the peripheral region (i.e., the Friuli Venezia Giulia region, as reported by Feudale et al., 2013). Therefore, we focus here on the NE Adriatic region, which consists of a section of the Croatian coast that covers the county of Istra and a few neighboring districts of the town of Rijeka. Geographically, the NE Adriatic region is surrounded by the Alps to the north, the Adriatic Sea to the west and south, and Dinarides to the east. Topographically, the Istrian Peninsula is characterized by a very complex terrain with flatlands to the south and west coasts, variable hills (up to 600 m high) with valleys in the central region, and mountainous regions (up to 1,400 m high) to the east and north. Therefore, the NE Adriatic region serves as a unique site for local analysis of hail properties across highly complex terrain.

By recognizing the current lack of knowledge of hail characteristics over the NE Adriatic, this study has two objectives. (i) The aim of this study is to provide an analysis of existing hail data and an estimation of the spatial hail distribution in the area of interest, which have not been previously conducted. (ii) A classification of the most frequent and relevant weather patterns in connection with hail reports is provided and reveals weather conditions during hail days. The approach adopted is based on the objective classification method, which allows for analysis of weather patterns not only of past observations but also of future data.
The paper is organized as follows. In section 2, we address the relevant data sources and uncertainties. In section 3, an overview of station data climatology is provided with an illustration of subareal differences (i.e., lowlands vs. mountainous regions) and an objective weather-type (WT) classification. Finally, section 4 provides a discussion and summary of our results.

2. Data and Methods

To adequately analyze the hail distributions and properties in Istria, two types of data are analyzed. The first data set contains hail observations collected from weather stations along the NE Adriatic coast and continental region of Croatia, as shown in Figure 1a, and this is considered to be a key source of information from which we derive multiple subsets of data to examine various hail characteristics. The second data set used is the ECMWF reanalysis ERA5 (Copernicus Climate Change Service [CS3], 2017), which has a horizontal resolution of 0.25° and is used to determine objectively defined weather patterns related to hail in the NE Adriatic region.

2.1. Hail Data Set

At the beginning of the last century, the Croatian Meteorological and Hydrological Service (DHMZ) started building a network of meteorological stations (i.e., main, climatological, and precipitation stations) around the country, and the majority of the stations were deployed between 1950 and 1981. While the exact number of stations in operation has varied over time, i.e., in 2017, 40 main meteorological stations with 2–5 professional observers provided hourly weather reports; 100 climatological stations with trained observers provided data at 7:00, 14:00, and 21:00 h local time (i.e., Central European Time, CET = UTC + 1 h); and 323 rain gauge stations with amateur observers conducted measurements at 7:00 h, all of the stations are required to provide daily logs of meteorological phenomena (e.g., cloudiness, fog, precipitation, and hail) and, when possible, the times, durations, and intensities of the recorded phenomena. All the collected data have passed quality control checks performed by the DHMZ, which have significantly reduced errors in the official data set. Quality control of the daily logs is performed in several steps. First, the information written in the logs for a particular day is compared to check for potential inconsistencies (i.e., on a sunny day and clear night, there was heavy rain, or yesterday, there was a thunderstorm with heavy rain and hail, but no rain was measured). When an inconsistency is identified, data from neighboring stations, radar sources, satellites, and other sources are used to determine the most likely scenario. When a likely scenario is identified, information from the logs is corrected. When the most likely scenario cannot be determined, information from the given station and day is rejected completely. We used official diary logs to extract all available information for hail events.

The acquired data set covers 35 available stations from the NE Adriatic region, which are shown in Figure 1b, and seven stations from the continental region of Croatia, which are indicated by the blue squares in Figure 1a. In the NE Adriatic region, we used data from one main observation station located in Pazin (circled in Figure 1b), eight climatological stations (triangles), and 26 rain gauge stations (crosshairs). The data set contains 1785 hail events recorded between 1948 and 2017. Following the methodologies of previous hail studies (Burcea et al., 2016; Ćurić & Janc, 2016; Tuovinen et al., 2009), hail reports were sorted into cases and days involving hail. A hail day is defined as a day with at least one hail report with a minimum diameter of 5 mm according to the definition of DHMZ and, suggestion of the World Meteorological Organization. A hail report becomes a unique hail case when no other hail reports exist within an interval of 15 min at nearby stations (less than 15 km). We also introduce hail frequency as a measure of the average number of hail days/year that occur at a particular station within the observation period. When considering this restriction, 1,518 cases over 951 days were identified. By classifying the hail data in terms of intensity and duration, we identified 899 cases with information on intensities and 1,118 cases with exact times. From a preliminary analysis of our data set, we conclude the following:

- Duration estimates are often rounded to 1, 5, 10, or 15 min, and hail tends to start on the 00th, 15th, 30th, and 45th minutes of the hour.
- Hail intensity records are subjective estimates made by an observer and are sorted into three categories: weak, medium, and strong. Intensity is separated in two groups, weak/medium intensity and strong intensity, to distinguish between smaller and larger hailstone sizes. Although there is no direct connection
between hail intensity and hailstone size, inspection of the official tutorial for observers and the weather diaries revealed that the majority of hail records that indicated strong intensities corresponded to hail sizes of 15 mm or larger and those that indicated medium intensities included sizes between 5 and 15 mm. After classifying the data by intensity groups, 24.9% of all the observed hailcases involved strong or potentially damaging intensity levels. This result is in accordance with the value of 23% described by Punge et al. (2014), which was based on the European Severe Weather Database (ESWD).

• Some stations lack continuous measurements for various reasons (i.e., due to a lack of observers for certain years or simply because an observer failed to report hail events), which means that there are gaps in the time series for some stations. Such issues are usually not detectable through systematic quality control due to the very low frequency of hail events, and to date, there has been no effective analysis of hail time series that may have highlighted such events.

To address the above uncertainties, we chose to exclude duration estimates from this study. The minimum time frame considered was 2 h. We elected to ignore potential misinterpretations of threshold sizes as there was no way to verify them because excluding all entries with weekly intensities would significantly reduce our data set. Since it was difficult to determine the exact sources of omissions and their actual durations, stations reporting very long periods without hail (e.g., more than 10 years) were excluded from the trend analysis. Stations reporting sporadic hail events (fewer than 10 entries over 60 years) were excluded from the data set. As a result, our main data set includes 27 stations reporting 1,469 hail cases. From our main data set, we defined three subsets to determine the spatial and temporal characteristics of hail over the NE Adriatic. From these data and the data set for the continental region, we created Table 1, which provides brief descriptions and contributions of each data set. Each data set is described in more detail below:

• The main data set (I) shown in Table 1 covers 27 stations in the region shown in Figure 1b. This data set includes the main observation stations, climatological stations, and 17 rain gauge stations. From this data set, annual and diurnal cycles and annual mean hail frequencies are calculated for each station. It is important to note that 12 of the 27 stations have missing data. To obtain hail frequencies for these 12 stations, we used only the longest time series with no omissions for each station.

• Data set II includes the five main meteorological stations and two climatological stations located in the NW region of Croatia (blue squares in Figure 1a). Topographically, the area includes a relatively complex terrain due to the presence of isolated mountain ranges and land-use patterns (e.g., farms and vineyards), which are similar to those found in Istria. However, the impact of the sea is small. This data set is compared to data set III to identify how much these regions differ.

• Data set III was derived from data set I by excluding all stations with data gaps. Only 14 stations remained and are indicated by the red dots in Figure 1b. These stations collected uninterrupted measurements from 1963 to 2017 and reported approximately 72% of the hail cases from data set I (1,094 cases of hail).
Thus, we use data set III to identify potential trends via linear regression and Mann-Kendall trend significance tests with Theil-Sen trend estimates.

- Data set IV includes 13 stations located along the western and southwestern coasts of Istria to 13 km inland. This data set represents the lowlands of the western region because the highest station is located at an elevation of approximately 250 m from the mean sea level.
- Data set V includes 14 stations located farther inland or are in the mountains of Istria, which are shielded from the direct influence of onshore flows. The above two data sets (Data sets IV and V) are used to examine the potential differences in the hail patterns between two areas with different levels of maritime conditions.

### 2.2. WT Analysis

We used daily mean ERA5 reanalysis data (1979–2017) to extract weather patterns related to hail events and identified 673 days with hail. We created an objective algorithm for WT classification based on the objective classification given by Bissolli and Dittmann (2001) and incorporated the subjective approach proposed by Poje (1965) to examine weather phenomena in Croatia. Our algorithm generally follows their recommendations, but we made changes to our determinations of advection types and vorticities. To determine advection types, we used 700-hPa horizontal wind component data and defined 36 possible wind directions that were shifted by 10° from each other (Bissolli & Dittmann, 2001). When two thirds of the grid points fell within one quadrant (i.e., 0–90°, 90–180°, 180–270°, and 270–360°), the center of the sector was defined as the wind index (in °). The program determined which main wind direction corresponded with the wind index (NE, SE, SW, NW, or UC unclassified), i.e., the prevailing wind direction. We conducted these computations over a smaller domain (20 points) that covered only the NE Adriatic region (Figure 1b) because, for the purposes of studying hail events, we are only interested in local wind features. The other algorithm uses large-scale parameters and runs over a larger domain that covers the entire Adriatic Region, part of the Mediterranean and the continental area (35–50°N, 5–21°E). The vorticity indexes for the upper levels were obtained from a weighted areal mean of $V^2\Phi_{500}$ (V^2 Laplace operator, $\Phi_{500}$ 500-hPa geopotential), and the vorticity values at the mean sea level were obtained from $V^2p$, where $p$ is the mean sea level pressure (mslp).

A quasi-nongradient field is present when the mean $Vp$ is less than 0.06 hPa/km. From the vorticity index, we obtained 17 different weather patterns, of which 16 corresponded to cyclones or anticyclones occurring near the surface, while one pattern represented a quasi-nongradient field (as proposed by Poje, 1965). All the cyclonic and anticyclonic weather patterns were defined as deep (a cyclone or anticyclone on the surface and a cyclone or anticyclone above the surface; in Figure 8, we use CC or AA, respectively) or shallow (a cyclone or anticyclone on the surface and an anticyclone or cyclone above the surface; in Figure 8, we, use CA or AC, respectively). Furthermore, with respect to our inner domain, we distinguished among the four sides of prevailing pressure systems: front, upper, back, and lower. A more detailed description is presented in Belušić Vozila (2018).

The thermodynamic indices were computed using the Sounding and Hodograph Analysis and Research Program in Python (SHARPpy) (Blumberg et al., 2017). SHARPpy is a collection of an open-source, upper-air sounding analysis and visualization routines. Based on the profiles of temperature, specific humidity, pressure, height, and wind components from ERA5 reanalysis, SHARPpy was used to compute lifted index (LI), most unstable CAPE (MUCAPE), K-index (KI), deep-layer shear (DLS), and freezing level height. ERA5 data from the surface and 17 pressure levels at 00:00, 06:00, 12:00, 18:00 UTC were used. LI was calculated as the difference between the temperature at 500 hPa and the temperature of an air parcel lifted moist adiabatically to 500 hPa from the surface. MUCAPE was assessed by lifting the parcel with the maximum equivalent potential temperature values in the lowest 400 hPa, i.e., the most unstable parcel. From the temperature difference between 850 and 500 hPa and the moisture content of the lower atmosphere, the KI was determined. DLS was determined as the difference in wind speed between the surface (10 m) and 6 km. Using linear interpolation, the temperature profile was obtained and the height (meters above ground level) of the 0°C isotherm was obtained. To obtain a comparison between indices on hail days and days without hail, we used the daily mean fields of indices averaged over the NE Adriatic region, as indicated by the black rectangle in Figure 1b.
Figure 2. Yearly numbers of hail cases (red) and hail days (blue) based on 14 stations (red dots in Figure 1b) from 1963 to 2017 (data set III). The solid horizontal lines represent average values, while the dashed lines indicate twice the standard deviations.

3. Results and Discussion

3.1. Multiannual Distribution

The distributions of hail days and hail cases for the Istria region (based on data set III) (1963–2017) show strong variations among years (Figure 2), which echo the findings of Tuovinen et al. (2009) and Ćurić and Janc (2016). On average, there are 14.2 hail days/year, as indicated by the horizontal blue line, and there are 19.9 hail cases/year (as indicated by the horizontal solid red line). The dashed blue and red lines represent twice the standard deviation of hail days and hail cases, respectively.

The greatest numbers of hail cases were observed in 1998 (43 cases) and 2014 (44 cases), when the number of cases exceeded two standard deviations from the time series average. However, there was no particular year in which the overall number of days showed great extremes. Furthermore, by following Ćurić and Janc (2016), we computed the linear (not shown) and Mann-Kendall trend significances with Theil-Sen trend estimates for hail cases and hail days. We used the 55 years of uninterrupted measurements in the NE Adriatic region from data set III (Table 1), and the results are shown in Table 2. At the annual scale, we detected a slight positive trend, but the significance level was low. However, a slightly positive and significant trend for both hail cases and days was visible for the spring season (MAM). There was also an indication of a slight negative trend in the summer season with a significance level of 0.93 for hail days and a significance level of 0.85 for hail cases. The warm and cold parts of the year did not show any significant trends, although the cold part exhibited a slight indication of a positive trend. However, after inspecting all other combinations, we found the periods with the most positive and most negative trends. The period with the most positive trend extended from November to May. This period had a moderate positive trend of 0.13 hail cases/year and 0.09 hail days/year, with a significance of 0.99. The most negative trend extended from June to October, but the signal was weaker and less significant. These results and the annual trend (which is positive but with weak significance) indicated that there is a redistribution of hail activity toward the spring and winter periods, while the summer period seems to exhibit gradually diminishing hail activity. This difference could be related to the systematic increase in the daily mean temperatures and warm spells

| Warm half | Cold half | Most positive | Most negative |
|-----------|-----------|---------------|---------------|
| April to September | October to March | November to May | June to October |

| Hail cases | Trend | 0.1 | 0.0 | 0.07 | −0.05 | 0.0 | 0.04 | 0.04 | 0.13 | −0.07 |
| Significance | 0.86 | 0.77 | 0.97 | 0.85 | 0.13 | 0.48 | 0.89 | **0.99** | 0.85 |
| Hail days | Trend | 0.06 | 0.0 | 0.06 | −0.04 | 0.0 | 0.0 | 0.03 | 0.09 | −0.06 |
| Significance | 0.79 | 0.83 | **0.98** | **0.93** | 0.16 | 0.41 | 0.89 | **0.99** | **0.93** |

Note. The results are based on 55 years of uninterrupted measurements in the NE Adriatic Region from data set III (Table 1). Trends with significance levels greater than 0.9 are shown in bold.
Figure 3. Illustration of the uncertainties of the hail data trend computations. Each point on the x-axis denotes a consecutive 30-year period of hail-day data obtained from dataset III. Each point shows the Mann-Kendall trend significance value in blue and the Theil-Sen trend estimate in red starting from the period 1963–1992, followed by the period from 1964 to 1993 etc. The black lines denote zero values, and 0.95 is the significance level.

During summer months, which raise the freezing level to higher altitudes and disturb hail generation. Such results are rather disturbing, since during spring, most agricultural products are most vulnerable and even weak hail can lead to substantial losses.

We would like to add another perspective to the trend analyses of the in situ measurements. Based on the in situ measurements (regardless of the temporal resolution), it is difficult to conclude whether a particular year has a high or low hail occurrence due to favorable weather conditions in general or whether convective systems more frequently passed over specific station locations. For the same reasons, any trend analysis of in situ data that suggests a positive or negative trend should be viewed with caution since it is difficult to distinguish between the above-mentioned cases. To illustrate the sensitivity of trend computations, we used consecutive 30-year periods from data set III (hail cases only) and included whole years. For each period, the Mann-Kendall trend significance was computed as well as the Theil-Sen trend estimate. Each period with single points showing trends and significances is shown in Figure 3.

Along the x-axis, each point represents a 30-year period starting from 1963–1992, followed by 1964–1993 and continuing to 1988–2017. Along the y-axis, the trend values (red) of a particular period vary from −0.15 to 0.45 hail cases/year, while the accompanying significance levels (blue) are shown on a scale of 0.0–1.0. A significance threshold of 0.95 is indicated by a black line. From Figure 3, we can see that there were 6 consecutive years for which the 30-year periods suggested very strong positive and significance trends. Positive trends were influenced mostly by the above average values of the annual hail day counts for the period 1995–2010 (Figure 2). The strongest trends and significances were detected for the period 1979–2008, with an increase of 0.45 hail days/year. However, upon extending the trend analysis for the full period (as shown in Table 2), no significant trend was found.

3.2. Annual and Diurnal Distribution

Data set I enabled analysis of annual and diurnal hail cycles over the NE Adriatic region. In Figure 4a, the annual cycles of hail frequency are shown for both hail days (blue) and hail cases (red). Most hail activity (70%) was concentrated in the warmer parts of the year (April–September), with a significant increase in April.

Figure 4. (a) Annual distributions of hail over the NE Adriatic region in terms of the monthly sums distinguished by hail cases (red) and hail days (blue) based on data set I. The numbers shown over the blue bars represent the ratios of hail cases to hail days, which is a rough measure of the spatial extent of hail swaths per day. (b) Diurnal distributions of hail cases separated by intensity based on data set I. The red bars denote moderate and weak hail events, and the blue bars denote strong hail events.
Hail is a very frequent feature during the summer months until August, while July is the most active month for both hail cases and hail days. Although the hail frequency decreases in autumn months, hail still occurs. We computed the ratios of hail cases to hail days (numbers shown in Figure 4a over the histograms), which serve as a rough measure of the spatial extent of hail swaths per day. These numbers suggest the presence of seasonal variations in the cases to days ratios. Higher ratios in spring and autumn than those in summer indicate the potentially different characteristics of convective development. To provide a more adequate explanation for the seasonal variability of the cases to day ratios, more detailed research using radar and simulations should be conducted. Due to its proximity to the sea, the Istrian region is affected by maritime conditions (warmer and wetter winters), and hail in this region is therefore recorded throughout the whole year. A minimum of 34 hail days was reported in January, although the overall winter period (DJF) included approximately 10% of all hail days, with 15 reports of strong hail cases. A local maximum also occurs in November. This maximum is close to September's hail day count (77 [November] vs. 87 [September]) and nearly equals the number of hail cases between November (137) and September (139); November includes local phenomena typical of the NE Adriatic region. Moreover, in the same month, more frequent waterspout formations have been observed near the Adriatic coast (Renko et al., 2016). This pattern may be associated with the peak in the annual precipitation cycle (i.e., cyclone activity) in November across stations along the coastal Adriatic region (Fig. 4.108 in Penzar et al., 2001). How and why these patterns occur is not yet fully understood and are beyond the scope of this paper; we leave investigations of this phenomenon to future work.

The diurnal distributions presented in Figure 4b show a comparison of hail cases based on intensity and sorted into two intensity categories. The red bars denote moderate and weak hail intensities, while the blue bars denote strong hail events sorted over 2-h intervals. While weak-intensity hail follows the daily heating pattern, with a maximum occurring at approximately 12:00 h, strong-intensity hail levels present two maxima that occur at approximately 12 (primary) and 16 h (secondary). Through further seasonal analysis (spring, summer, fall; not shown), we determined that the 12-h maximum occurs in summer, while the 16-h maximum occurs in spring. The afternoon maxima for strong hail can be related to the postponed convection that results from various causes (Tuovinen et al., 2009), which allow systems to develop larger hail. This situation may, in part, be linked to the warm-moist SW advection of large convective systems in front of cyclones or to troughs observed not only in summer (Mikuš et al., 2012; Poljak et al., 2014).

In reference to Istria, various studies have shown that due to the mountains in the hinterland area, convection usually starts somewhere inland in the late morning hours (e.g., Babić et al., 2012; Feudale et al., 2013; Kehler-Poljak et al., 2017; Poljak et al., 2014). The convex shape of the peninsula contributes to the development of local winds (particularly in summer) that often form a centrally placed convergence zone in the wind field (Kehler-Poljak et al., 2017; Telišman Prtenjak & Grisogono, 2007; Telišman Prtenjak et al., 2006). Interactions between gust front(s) and local convergence zone(s) are neither unusual nor rare (Poljak et al., 2014). Since convection development is supported by mountains to the north and east and by near-surface wind convergence (i.e., which reflects constant forcing), under favorable midtropospheric conditions (e.g., Sow et al., 2011), convective cells tend to circle over the peninsula and reach coastal areas later in the day. Such circling and drifting result in the occasional merging of systems and can generate the potential for stronger hail, which may contribute to both of the observed maxima. However, further research is needed.

Despite the data quality measures applied, observers may have misinterpreted hail size and reported dense, small hail as strong hail, contributing to the maxima. Unfortunately, we were not able to exclude such cases from the analysis.

### 3.3. West Coast Versus Inland Distributions

Our data are fixed to the latitudes/longitudes of the observation stations, which deprive us of a dense, regular spatial distribution; data sets IV and V represent reasonable selections of stations for examining potential spatial differences. Considering Istria's orographic profile (from Figure 1), coastal stations from the west to southwest were separately examined and then compared to those located in the interior of Istria. We recorded 732 cases over 557 days across the inland stations and 480 cases over 354 days along the western coast.

The annual cycle shown in Figure 5a confirms that the hail season in both areas occurs throughout the year, with an expected increase in hail activity occurring during the warmer part of the year (April–September) in both data sets. However, the inland area (blue) shows a more rapid increase in hail activity at the start
Figure 5. Distributions of hail cases from data sets IV and V represented by the monthly sums for west coast sites (red) and inland stations (blue) (a) at the annual scale and (b) at the daily scale.

of April, with a sharp increase occurring in May and decline occurring in September, while the west coast (red) shows a more gradual increase, with a 2-month delay starting in June, a peak occurring in July and a reduction occurring after September. A November maximum is visible in both data sets. For daily cycles, Figure 5b shows the following. While the inland area (blue) shows the already-observed noon maximum with prolonged afternoon activity (similar to the data shown in Figure 4b) and produces over 80% of hail cases that occur between 10:00 and 20:00 h, the west coast (red) includes only 60% of hail cases in the same period. The west coast also exhibits a less-pronounced and variable daily cycle, with three maxima occurring at approximately 08:00, 12:00, and 16:00 h, and prolonged afternoon activity until 20:00 h. The first maximum, which occurs at 08:00 h for a certain number of cases, can be associated with a local circulation wind regime, especially with offshore flows occurring between the convex coastline of the peninsula and mainland. Under such conditions, a wind field convergence zone over the sea may form (Trieste Bay; see Figure 1) and contribute to other conditions that favor the development of an early morning deep convection. Such conditions over Trieste Bay were not analyzed in detail (e.g., by numerical simulations) but have been observed from lightning distributions over the NE Adriatic region (Fig. 6a in Feudale et al., 2013). Some thunderstorms have been observed in similar locations in the Mediterranean (Mazón & Pino, 2013). It is also interesting to note that the morning maximum of coastal hail cases overlaps the typical observation times of waterspout occurrences (9–10 CET), as noted by Sioutas and Keul (2007) and Renko et al. (2016). The noon maximum is probably linked to the daily heating cycle over land. Some studies have shown that topographical characteristics, such as the heights, shapes, and available surfaces of (limited) land areas, determine the timing of cloud mergers and convection intensities (e.g., Mahrer & Segal, 1985; Saito et al., 2001). The inland convective drift toward the coastal area may influence the 16:00 h maximum.

The differences in hail activity between the west coast and inland area shown above are consistent with other characteristics of weather and climate of this region. Zaninović et al. (2008) indicated that the significant differences between the western coast of Istria and inland were exhibited in the temperature, precipitation, water vapor, air humidity, solar radiation, insolation duration, and cloudiness fields. Based on the 2-m temperatures (mean, min, and max), precipitation, relative humidities, and wind speeds, Omazić et al. (2020) have calculated bioclimatic indices for present and future climates. Their results (maps) clearly show a distinct difference between the coastal and inner regions for both present and future climates.

3.4. Spatial Distribution of Hail

Using the hail frequencies from data set I and inverse distance weighted interpolation, the 2D spatial distribution of the average hail days per year was calculated (Figure 6). The spatial distribution points to three hot spots in areas with more than 1.7 hail days/year. At the center of Istria, where the main meteorological station is located (Figure 1b) (blue circle), we find hail frequencies of 1.75 hail days/year. This station is located at 285 m and is surrounded by local hills of up to 500 m, which appear to contribute to the enhanced convection levels, as was observed for the NW part of Croatia (Počakal et al., 2018). The strongest hot spot is located NNE of the main meteorological station.

The station here is located along mountain canyons with an approximately 670-m elevation and is surrounded by mountain peaks of up to 1,030-m elevation; the station is favorably positioned for detecting orographic deep, moist convection. We measured a frequency of 2.8 hail days/year. A third hot spot is located
ENE from the main station. This station is located along the interior side of the mountain pass at approximately 950 m. The mountain pass forms the lowest point in the area; thus, moist air from both sides is likely channeled through the pass and increases the likelihood of hail to 2.1 hail days/year. Between these hot spots, several cold spots appear with frequencies of less than 0.5 hail days/year. While the coastal zone experiences less hail, especially in the southern region, most of the area reports frequencies of approximately 1 hail event/year or greater. When we consider the overall distances between stations (up to 10 km on average), hail shows a very strong pattern of spatial variability, even at local scales, where the terrain is complex. Similar results have been found by other studies based on radar estimates, such as Nisi et al. (2016) and Strzinar and Skok (2018). While radar-based distributions reflect hail patterns across all the locations measured with radar, a qualitative comparison of our results with the radar-based hail climatology of the broader area of Slovenia (the lower part of Fig. 8b from Strzinar & Skok, 2018) reveals an overlay of the identified northern hot spot location.

3.5. Comparison of Continental and Istrian Regions

To compare two regions with different numbers of stations and different areas, we normalized our values for hail days by the number of stations. We used the same observation period, and the final values represent the average number of hail days per station based on data sets II and III. Figure 7 shows the annual and diurnal cycles of the continental (blue) and Istrian (red) regions, respectively. First, only minor differences between the annual and diurnal cycles of data sets I (Figure 4) and III (Figure 7, red bars) were found as a consequence of data reduction. The goal of this section is to identify approximate differences and similarities.
between the two regions and provide estimates of general hail activity rather than conducting monthly or hourly comparisons.

The hail season in the continental region is 2 months shorter than that in Istria and starts in May and ends in August. The season is similar to that in the NW part of Croatia (Figure 4 in Počakal et al., 2009), but it should be considered that we used only part of the continental region and different data sources and periods. Hail activity is also more concentrated in the warmer parts of the year (86% of all hail days), especially from May to August, which accounts for 75% of the observed hail days. In the diurnal cycle (Figure 7b), a very clear afternoon peak occurs, with 85% of hail cases occurring between 10:00 and 20:00 h, suggesting that the hail patterns are strongly related to the daily heating patterns, which also resemble the diurnal distribution of hail presented in Fig. 6 from Počakal et al. (2009). High-intensity hail occurs at approximately 16:00 h, while low and moderate intensity hail events present their maximum at 14:00 h (not shown), which corroborate the results of Tuovinen et al. (2009). A further comparison of the intensity of the hail cases presented here shows additional differences. For data set III, 30% of hail cases are of high intensity, but such events represent only 18% of the cases in data set II (not shown). Such differences in intensity might be attributable to the hail suspension network, which has been active since 1980, although no clear signs of such a pattern are visible in our data set. In contrast to the observations for the Istrian region, strong hail is not recorded during the DJF season in the continental area.

3.6. Weather Types

By analyzing all the WTs for the period available from the ERA5 reanalysis data (1979–2017), we obtained a general picture of both circulation patterns with a limited dominance of cyclonic systems (48%), followed by anticyclonic systems (42%), while the remaining 10% were recognized as quasi-nongradient systems (Figure 8a). The most dominant signal was observed from the deep anticyclonic systems located above our
domain (56% within anticyclonic WTs). In contrast, cyclones were more evenly distributed, with WT3s exhibiting the rarest occurrence.

From data set I, we extracted all the hail days for the studied period (1979–2017) and computed the WTs for each day (Figure 8b). We used numbers to differentiate between positions and types (e.g., WT1, WT2, WT3, and WT4 for the front, top, back, and lower sides of cyclones affecting the Istrian region, respectively, and the same for WT5–8 for anticyclonic systems). Colors denote the system intensity levels (high intensities are indicated by red bars, and low intensities are indicated by blue bars). In Figure 9, we show composites of high-intensity WTs, including the wind vectors from 700 hPa, and for comparison with Figure 10, we show strong-intensity WTs on hail days.

**Figure 9.** Composite of surface pressures (depicted for every 2 hPa) and winds (based on ERA5 data for all days) involving strong intensity weather types; each subfigure shows the WTs shown in the lower right corner, and a 10 m/s reference vector is added in the upper left corner. The boundary between low- and high-pressure formations is 1,016 hPa based on the climatological average for our domain.
Figure 10. As in Figure 9 but for hail days.

Figure 8b shows that approximately 78.5% of hail can be attributed to cyclonic activity, which is expected since cyclonic weather provides a good source of lift, higher values of CAPE and favors moist air advection (Santos & Belo-Pereira, 2019). Furthermore, 14.5% of hail is attributed to anticyclonic activity and 7.0% is associated with quasi-nongradient activity. WT4, which represents the lower sides of deep and shallow cyclones, is found to be associated with 46% of all cyclonic hail days (Figure 8b). When we compare our hail WTs to the distribution of the 17 WTs for the whole period, we obtain the percentage hail occurrence for a particular WT (Figure 8c). In contrast to what is shown in Figure 8b, hail occurs most frequently along the backs of shallow cyclonic systems, although this particular WT occurs very rarely. Figure 8b shows only 14 hail days (WT3 blue). On the other hand, a deep cyclone in WT4 (see also Figure 10, WT4) has a 15% chance of producing hail over the observed area. The front sections of deep cyclonic systems (Figure 10, WT1) present a greater than 13% chance to generate hail, while anticyclonic WTs present a 5% chance...
Figure 11. Relative frequencies of advection types (according to the prevailing winds at 700 hPa over the Istria region) for the hail days included in the ERA5 reanalysis data (1979–2017), which are denoted by the red bars, and all days, which are denoted by the blue bars. In this figure, the abbreviations are as follows: NE = northeastern wind; NW = northwestern wind; SE = southeastern wind; SW = southwestern wind; UC = unclassified wind.

(WT5 and WT6) or less. However, composites of anticyclonic WTs on days with hail (Figure 10) still provide environments for hail generation. WT5 and WT8 both have NW wind components over the NE Adriatic region, which may advect colder air masses and produce unstable environments that are favored by convection, while WT6 shows SW advection. We should note that hail that occurs during a specific WT can also be misinterpreted due to the occurrence of fast-moving smaller low-pressure systems that can produce several WTs within a single day. Unfortunately, we were not able to account for these variations with our algorithm, as we used daily mean data; thus, our algorithm emphasizes WTs with the strongest signals (on a particular day).

The advection types at 700 hPa, as described in section 2.2, are shown in Figure 11 for all the days of the ERA5 period (blue bars) and for the hail days (red bars) of the ERA5 period. The y-axis shows the relative frequencies of particular advection types relative to the total number of advection types. In general, SW winds are dominant for both all days and hail days and are associated with 55% of all hail events, which is reasonable and expected since such air masses come directly from the Mediterranean Sea and Adriatic Sea. Such distributions for both all days and hail days correspond well with the wind directions composite shown in Figures 9 and 10 in combination with Figure 9a if we consider the NE Adriatic region. In particular, WT1, WT4, WT6, and NG-WT hail days all have mean wind vectors located in the SW quadrant. Additionally, our results agree strongly with the subjectively applied classifications of the WT and flow conditions for days with deep convection provided by Mikuš et al. (2012) when analyzing lightning climatology. In that paper, in the area that includes Istria (which is somewhat larger than that examined in this study), lightning usually occurs as a result of low-pressure formation (e.g., cyclones and troughs) on approximately 3/4 of days with deep convection. Furthermore, the prevailing large-scale wind regimes are traced from the southwest for half of the days and NW winds on 1/4 of the days during which lightning occurs, echoing the results for this region for days with hail.

Figure 12. Box and whisker plot comparisons of the instability indices on days with hail from dataset I (in red) and non-hail days (in blue). The median values are shown by the horizontal lines in the boxes; box edges are the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles. (a) Lifted index at 500 hPa (°C); (b) most unstable CAPE (MUCAPE, J/kg); (c) K-index (°C); (d) deep-layer shear (DLS, m/s) in the lowermost 6 km; and (e) freezing level height (0° height, m).
Figure 13. Scatter plot of the MUCAPE (J/kg) and DLS (m/s) values for hail days from (a) data set I and (b) nonhail days. The color bars indicate the probability of a particular parameter combination within the observed set. We note that the total number of hail days was 673, while there were 13,571 nonhail days.

Additionally, we extracted the values of all the indices for days with hail and compared them with those for all nonhail days using the box and whisker plots shown in Figure 11. The red boxes represent hail days, while the blue boxes represent nonhail days. The median values are the horizontal lines in the boxes, the box edges are the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles. All the indices show the differences between hail days and nonhail days. The most significant differences are for LI, MUCAPE and KI. Low LI values and high MUCAPE and KI values confirm that hail forms in a very unstable environment with moderate to high wind shear. The MUCAPE values roughly correspond to those shown in Púčik et al. (2015), who used radiosonde data and ESWD data to examine severe environments. The results for 0° height (Figure 12c) confirm that all the hail events recorded by observers had acceptable freezing level heights. The absolute minimum of the mean daily freezing levels on days with hail was 645 m (not shown), and 95% of hail days had a mean daily freezing level higher than 1,160 m. On the other hand, there is also an upper limit of freezing level height (e.g., 4,000 m) above which no hail was reported. Such results reinforce our previous findings that hail activity in the NE Adriatic region is, in fact, present throughout the year.

When dealing with severe environments, CAPE/MUCAPE and DLS are frequently used indicators of severe weather (e.g., Púčik et al., 2015; Santos & Belo-Pereira, 2019), and their combination often highlights the thresholds for severe weather occurrences. We compared these two parameters for both hail days (data set I) and nonhail days, and the results are shown in Figure 13. Each colored square shows the probability of a particular parameter combination within the observed set. For low DLS values (<10 m/s) on hail days, we observe MUCAPE values between 700 and 1,100 J/kg, while larger values of DLS are associated with smaller MUCAPE values (300–800 J/kg) for hail generation. There are only a few events (less than 2%) for which very small MUCAPE values are associated with high DLS values. In comparison with nonhail days (Figure 13b), the majority of events are associated with very small MUCAPE values. There is, however, a local MUCAPE maximum at 650 J/kg that is associated with DSL 10 m/s. It could be that these environments are connected to strong precipitation events or the appearance of some other types of extreme weather, e.g., waterspout occurrences (Renko et al., 2016). However, this hypothesis needs further analysis and extends beyond the scope of this study.

4. Conclusions

We analyzed data acquired from two independent data sources to identify the spatial and temporal aspects of hail in the NE Adriatic region and to highlight the WTs responsible for this hail. The main conclusions from this analysis are as follows.

(i) Station measurements show strong spatial and temporal variability of hail occurrences across the studied domain. We identified three hot spots in our domain with frequencies of 1.75–2.8 hail days/year and several cold spots with frequencies of less than 0.5 hail days/year. Trend analysis revealed a slight but insignificant increase in yearly hail activity. However, it detected a redistribution of hail among the seasons (e.g., MAM, JJA, SON, and DJF), especially between MAM and JJA. While the JJA season and the June–October period recorded negative significant trends similar to reports of the stations measurements (Punge & Kunz, 2016), the period from November to March exhibited a positive trend with a 0.99 significance level. Trend analyses also showed high levels of sensitivity to the selection of the studied period, suggesting that very long time series are needed.

(ii) On the annual scale, hail occurred throughout the year, with most events occurring in the warmer months. However, some stronger events were sporadically reported in the cold(er) times of the year. In addition, a local maximum of hail events was detected in November across all data sets and time periods. Such a signal seems to be influenced by the Adriatic Sea, as it coincides with a local maximum in waterspout appearances along the entire Adriatic coast (Renko et al., 2016) and has not been reported for the continental region of Croatia. Two maxima in the diurnal cycle for strong hail (12:00 and 16:00 h) and three maxima of hail over the coastal area (08:00, 12:00, and 16:00 h) were also observed. When we consider the orographic configuration of the region and the dominance of the SW advection type...
for hail generation, most hail activity that occurs in the interior parts of Istria is presumably orographically induced. Additionally, often influenced by the northern and eastern mountains and by local wind regimes, convective clouds that form over the peninsula may drift over Istria and create new cells during their life cycle.

(iii) Convective clouds may often move toward the lowlands of the west coast and especially to the NW regions, where we found higher levels of hail activity relative to the SW part of the coast. The morning (08:00 h) maximum is probably influenced by differences in overnight sea and land cooling. Still, it is necessary to conduct further detailed analyses of hail days using numerical simulations.

(iv) Objectively derived WTs provide strong insight into synoptic activities, which are responsible for hail in the NE Adriatic region. Most hail events are related to cyclonic WTs and to events starting at the lower and front parts of cyclones. Approximately 55% of hail is associated with SW wind advection, which is found in WT1, WT4, and WT6 (Figure 10). Anticyclonic WTs associated with hail still offer reasonable results and suggest colder air advection from the NW. Additionally, the instability indices confirmed that the majority of hail days fall under highly unstable (MUCAPE between 600 and 1,000 J/kg) and sheared (DLS between 8 and 20 m/s in the first 6 km) environments that correspond with the WT classification and assure the quality of the observed data.

Data Availability Statement

Data for this research was obtained from three sources. ERA5 data are available online (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) (Copernicus Climate Change Service, 2017). The new hail data can be available through inquiries through the following links (https://meteo.hr/proizvodi_e.php?section=proizvodi_usluge&param=services), since the data used fall under the data policy of the Croatian Meteorological and Hydrological Service; for more information, please contact the following (usluge@cirus.dh2.hr).

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Erratum

In the originally published version of this article, Figure 8 did not include a section of the right side of each subplot, namely a label of “NG-WT.” Figure 8 has since been corrected, and this version may be considered the authoritative version of record.