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Key Points:
- Based on a logistic hail model, well-known hail hot spots can be identified in Europe
- The hail potential shows large annual and multiannual variability but no overall trend
- Conditions that favor hailstorms are controlled by large-scale circulation patterns and mechanisms

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Hail potential in Europe based on a regional climate model hindcast

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Abstract Due to the local-scale nature of hail and a lack of appropriate observation systems, comprehensive, reliable, and consistent information about hail frequency and intensity in Europe is not available. To overcome this constraint, we developed a logistic hail model that quantifies the potential of the atmosphere to form hailstorms. The model is based on a combination of appropriate hail-relevant meteorological parameters. This paper presents the application of an adjusted version of the logistic model with the objective being to estimate the hail potential across Europe based on dynamically downscaled National Centers for Environmental Prediction/National Center for Atmospheric Research1 reanalysis over a long-term period of 60 years (1951–2010). The model output, in terms of the potential hail index (PHI), identified several hot spots that are well known from other observational studies. Time series of the PHI over the 60 year period show a high correlation at different sites across Europe and high annual and multiannual variability, but no overall trend.

1. Introduction

Severe hailstorms frequently cause considerable damage to buildings, crops, and automobiles, resulting in large monetary costs in many parts of Europe and the world. For example, two supercells in Germany on 27/28 July 2013 caused an insured damage of U.S. $3.7 billion (economic loss: U.S. $4.8 billion), representing the highest insured loss event worldwide in 2013 [*Munich Re*, 2014]. Despite the large damage potential associated with large hail in the order of billions of U.S. dollars, knowledge about the local hail frequency is still limited. Furthermore, the scarce availability of reliable hail observations hampers statistical analyses of long-term variability, including trends over recent decades. The main reason for this peculiarity is the local-scale extent of hail-affected areas, denoted as hailstreaks, in combination with a lack of appropriate monitoring systems.

An approach for tackling this problem is to identify appropriate large-scale parameters that favor hailstorm development (e.g., thermal instability or wind shear) and to use these parameters as proxies for hail [e.g., *López et al.*, 2001; *Manzato*, 2003; *Brooks et al.*, 2003]. Over Central Europe, for example, trend analyses of several sounding-derived convective parameters related to hail suggest an increase in atmospheric instability over the past three decades [*Mohr and Kunz*, 2013]. Large-scale weather patterns that favor hailstorms in Germany were found to have increased in the last 30 years [*Kapsch et al.*, 2012]. However, various meteorological and convective parameters related to thunderstorms are available, and it is still not clear which one is most appropriate for quantifying the convective potential of the atmosphere. To overcome this problem, and to improve the diagnostics of hail events, *Mohr et al.* [2015, M15 hereafter] combined different appropriate parameters by means of a logistic hail model (LHM) with the objective being to estimate the number of days where an increased hail probability may be present. The model version applied to Germany includes surface-based Lifted Index (SLI), large-scale weather types, 2 m temperature (T_{2m}; all three parameters at 12 UTC), and 2 m minimum temperature in the morning (T_{min}). These parameters, which were found to have the highest prediction skill for hail-producing thunderstorms, reflect thermal stability and near-surface properties in terms of temperature and moisture in the morning and early afternoon. The model output of the LHM is referred to as the potential hail index (PHI). As shown by M15, PHI quantified from reanalysis shows a high relation to both building insurance data and hail signals derived from radar reflectivity in Germany. However, since the PHI quantifies only the atmospheric potential for hailstorms to occur or not but does not consider triggering mechanisms such as low-level flow convergence, a direct comparison with hail observations is not possible. In that sense, the results of the PHI cannot mirror the real convective potential at single grid points but can do it for larger areas.

The main objectives of this study are to develop a modified version of the LHM, denoted as modLHM, that can be applied to Europe and to estimate large-scale spatial variability and long-term changes in the hail potential. Due to the latter objective, we employed regional retrospective hindcast that is available for Europe over a 60 year period.

2. Data Sets

Hailstorms in Europe occur most frequently in warm summer months [e.g., *Giaiotti et al.*, 2003; *Webb et al.*, 2009; *Berthet et al.*, 2011] in the afternoon between 12 and 16 UTC [*Tous and Romero*, 2006; *Kunz and Puskeiler*, 2010]. Therefore, we consider in our study a 3 month period from June to August and base the analysis on the preconvective environment at 12 UTC, which is around 12 LT in Ebro Valley (Spain) or 13:15 LT in Budapest (Hungary).

2.1. Regional Climate Model Run

The regional retrospective analysis, or hindcast, used in this study was carried out by the Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research using the COSMO (Consortium for Small-Scale Modelling) model in climate mode, COSMO-CLM Version 4.8 [*Rockel et al.*, 2008]. This regional climate model run, referred to as coastDat2 [*Geyer and Rockel*, 2013; *Geyer*, 2014], was driven by the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis (NCEP/NCAR1) data [*Kalnay et al.*, 1996]. The main advantage of this run is that the data assimilation procedure remained essentially unchanged during the project, so that trends due to an increased incorporation of observational data sets are minimized making the simulations most suitable for long-term statistical analyses. For the sake of improved reproduction of the large-scale circulation, the method of spectral nudging was applied via dynamical downscaling [*von Storch et al.*, 2000]. The coastDat2 runs are available from 1948 (including 3 years spin-up time) until today, with a horizontal resolution of 0.22° (~24 km) and 40 vertical model layers. In our study, we considered the 60 year time series from 1951 to 2010.

2.2. Verification Data

The scarce availability of direct hail observations and a general lack of intensity information hamper a thorough validation of the modLHM. A possibility to assess the prediction quality of the model is a comparison with other proxies such as hail signals derived from radar reflectivity, which is available for the whole area of Germany. For this purpose, we used the hail frequency assessment of *Puskeiler* [2013], who estimated hail signals from a combination of model data, lightning information, and three-dimensional radar reflectivity (radar composite of the German Weather Service, DWD) using an adjusted version of the *Waldvogel et al.* [1979] criterion. The data are available for the summer half year from 2005 to 2011 on a 1×1 km^2 grid. The results show a high relation to building insurance data (considered only damage yes/no) as expressed, for example, by a large Heidke Skill Score (HSS) [*Heidke*, 1926] of 0.70 on average. In our study, we considered the radar-derived hail frequency assessment between 2005 and 2010 to determine whether a specific day was a hail day or not. Over the whole investigation area, hail signals were obtained on 364 days, that is, on 66% of all days within the considered time frame.

3. Modified Logistic Hail Model

The LHM of M15 is based on the method of logistic regression [*Hosmer and Lemeshow*, 2000] and estimates the occurrence probability p of an event on a daily basis as a function of different meteorological quantities $\{x_1, x_2, \dots, x_n\}$ as independent variables:

$$y = p(x) = \frac{1}{1 + e^{-g(x)}} \qquad \text{with } 0 \le p(x) \le 1, \tag{1}$$

with the linear regression approach:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n, \tag{2}$$

where $\{\beta_1, \beta_2, \dots, \beta_n\}$ are regression coefficients.

Because hail-related and hail-unrelated objective weather types [*Kapsch et al.*, 2012] considered in the LHM refer to only a limited area, this parameter cannot be implemented in the model when it is applied to all of Europe. Therefore, the regression equation (equation (2)) of the modLHM is reduced to the following:

$$g_{\text{hail}} = \beta_0 + \beta_1 \cdot \text{SLI} + \beta_2 \cdot T_{\text{min}} + \beta_3 \cdot T_{2\text{m}}, \tag{3}$$

$$\text{whereas} \quad p_{\text{hail}} = \begin{cases} < 0.2 & , \quad \text{hail: NO} \\ \geq 0.2 & , \quad \text{hail: YES} \end{cases} .$$

The threshold of 0.2 was chosen by M15 since it yields reliable results by means of the receiver operating characteristic (ROC) curve. The regression coefficients β_n of modLHM are calibrated in the same way as in the original LHM (for details see M15) using ERA40 reanalysis, which was dynamically downscaled with COSMO-CLM (referred to as IMK40). The calibration was performed for the state of Baden-Württemberg (southwest Germany) between 1992 and 2000, where damage and inventory data from a building insurance company as the only information about hail on the ground are available. The application of the same calibration methods and incorporated data sets enables a direct comparison of the results obtained by the LHM and the modLHM.

Because the β coefficients differ slightly from one grid point to another, we considered not only the modLHM with the best prediction skill but used an ensemble consisting of 11 modLHMs to account for the LHM-dependent uncertainty of the results. Sensitivity tests performed in M15 showed that the size of the ensemble is not highly relevant for the results. The ensemble selection is described in detail in M15. Note that the average β_n values of the 11 modLHM including their standard deviations ($\beta_0 = -2.41 \pm 0.58$, $\beta_1 = -0.34 \pm 0.05$, $\beta_2 = 0.33 \pm 0.03$, and $\beta_3 = -0.21 \pm 0.04$) differ only slightly to those of the LHM (on average, ± 0.02; see Table 3 in M15).

As shown in M15, each meteorological parameter considered in the LHM/modLHM requires a bias correction prior to the incorporation in the model. This correction is necessary since the LHM/modLHM, and thus the individual regression coefficients β_n, have been specifically adapted to the climatological conditions that are prevalent in the original reanalysis run used for the calibration. The corrections are based on a comparison of the respective frequency distributions estimated from both data sets for the entire investigation area and the complete time series. For SLI, the (multiplicative) correction factor was 0.9 K, for $T_{2\text{m}}$ it was 1.02 K, and for T_{min} we found a combination of multiplicative and additive factor of 0.85 K+1.5 K that best corrects the data. Sensitivity tests based on subdivision of the data in both space and time show a fairly robust behavior (constant bias values) of the bias correction (not shown).

4. Climatology and Model Verification for Germany

To verify the results of the modLHM applied to the coastDat2 run, we only considered grid points within Germany during the period 1971 to 2000. The quantified mean annual PHI shows a pronounced north-to-south gradient, with the highest values present in the south (Figure 1a). An increased hail potential is estimated between 14 and 16 days per year in the northern and central parts of Germany, while it is between 18 and 28 days in the south (i.e., between 19.6 and 30.4% of all days in the summer). Maximum values (26 to 28 days) are found along a line from Lake Constance to east of Munich. Averaged over all grid points in Germany, the mean annual PHI is 16.8±3.5 days (i.e., 18.3±3.8% of all days in the summer).

The spatial distribution of the PHI derived from the modLHM using coastDat2 resembles that of the original LHM with IMK40 (Figure 1b), especially with regard to the large-scale gradient. Overall, the former produces slightly higher values between 2 and 4 at around three quarters of the grid points. The overestimation of 20 and 40% produced by modLHM applies to particular grid points between 9° and 13°E. This can be ascribed to the slightly varying spatial distribution of the climatology of each meteorological parameter and the resulting combination in the two models, modLHM and LHM. Furthermore, on the local scale, some additional discrepancies can be identified. The most striking is the pronounced maximum near the southern border for coastDat2, which is not found in the same strength in IMK40. Several other local-scale discrepancies can be attributed to the lower horizontal resolution of coastDat2 compared to IMK40 (0.065°). Thus, local-scale variability such as minima and maxima related to orographic effects are less pronounced in the former run.

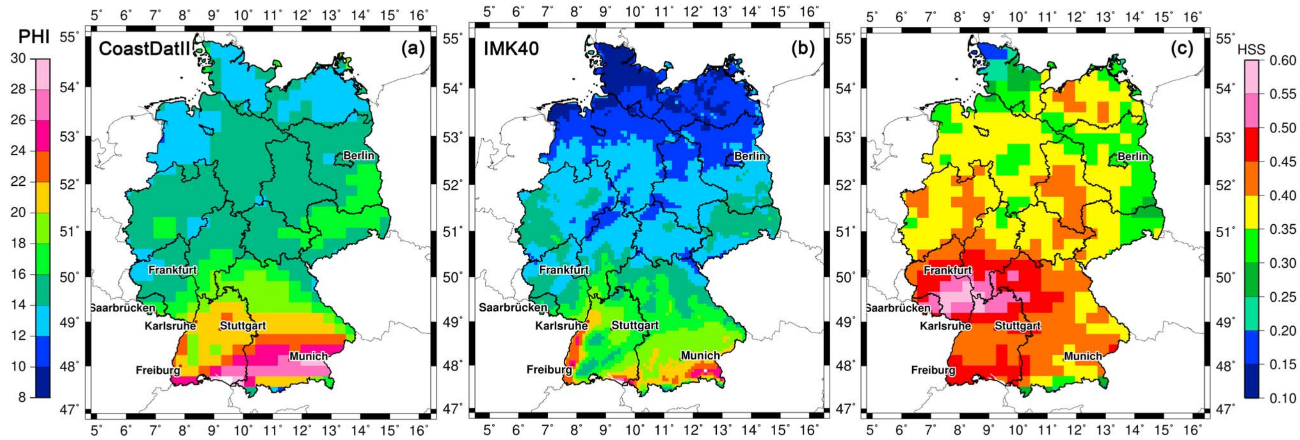

Figure 1. Median of the annual potential hail index (PHI) derived from (a) coastDat2 based on the modified logistic hail model and from (b) IMK40 based on the original logistic hail model from M15 (1971–2000). (c) Validation of the modLHM per Heidke Skill Score (HSS) with hail signals from radar data within a detection radius of 100 km (2005–2010).

That applies, for example, to the local minimum seen between the cities of Freiburg and Stuttgart or to the maximum in the upper Rhine valley between Karlsruhe and Freiburg.

In the next step, we verify the results of the modLHM with hail signals identified from radar data within a certain radius around each grid point of the model. Since the LHM/modLHM only estimates the potential for severe convection but does not consider any mechanisms relevant for convection initiation, we defined a rather large search radius of 100 km. By using the method of categorical verification, we quantified basic skill scores such as the probability of detection (POD), the false alarm rate (FAR), the Heidke Skill Score (HSS), and the Peirce Skill Score (PSS) computed from a 2×2 contingency table [*Wilks*, 2006]. HSS values above 0.35 at most of the grid points confirm the reliability of the PHI to estimate hail frequency (Figure 1c). Only in the very far north, where hail occurs only rarely, and in the northeast are the results of the PHI less reliable as indicated by HSS values below 0.3. The spatial distribution of the HSS shows a distinct north-to-south gradient, with the highest values up to 0.57 in the region between the cities of Saarbrücken, Frankfurt, and Karlsruhe. Mean values for all of Germany are: HSS = 0.40, PSS = 0.53, POD = 0.52, and FAR = 0.45. These skill scores are substantially higher compared to the results obtained in M15. A plausible—but not verified—explanation for the better performance of coastDat2 may be the applied technique of spectral nudging, which keeps the large-scale conditions close to the driving model, while internal smaller-scale features are allowed to develop. It has been shown that this method often yields a better representation of meteorological fields [e.g., *von Storch et al.*, 2000; *Feser et al.*, 2011].

5. Climatology and Trends in Europe

Applied to coastDat2 for most of Europe (1951–2010), the modLHM estimates the highest hail potential for northern Italy (Po Valley: 35 to 50 days), followed by a larger area north of the Alps (northern Switzerland, southern Germany, and parts of Austria) and to the east (Hungary and Serbia) with a total duration of 25 to 32 days (Figure 2a). In the northern countries, where prevailing colder and dryer air masses increase atmospheric stability, hail has an increased probability only on a few days. Lower PHI values are also found over large mountain chains such as the Alps, Pyrenees, Apennines, or Dinaric—mainly due to lower near-surface temperatures. Several grid points with high PHI values at the Mediterranean coastline are presumably not reliable. In that area, T_{min} is overestimated by the model due to the large heat capacity of the ocean and, thus, does not accurately represent the moisture content within the boundary layer.

Linear trend analyses, including trend-free prewhitening according to *Yue et al.* [2002] for the period 1951–2010, show changes in the PHI primarily around ± 3 days over the entire period (Figure 2b). Increasing PHI values are apparent for parts of Spain, France, Great Britain, Switzerland, and Austria, while in the eastern parts the trends are predominantly negative, with values between -1 and -11 days. However, at most of the grid points the trends have a statistical significance below 95% according to the nonparametric Mann-Kendall test (two sided; hatched in Figure 2b). Significant trends are found only for limited regions in the northeast

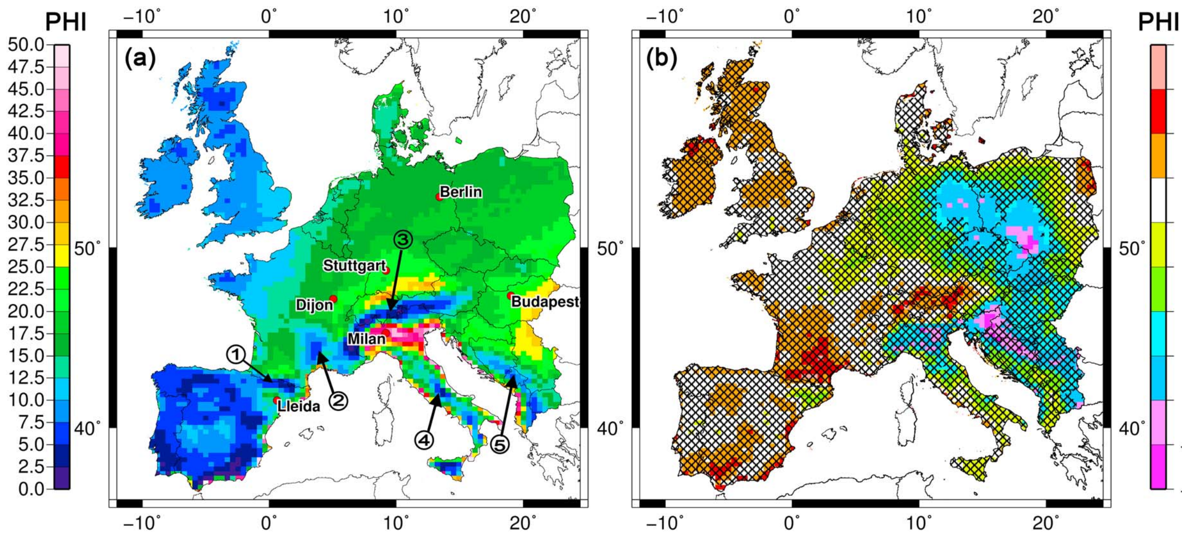

Figure 2. (a) Median of the annual potential hail index (PHI) based on the modified logistic hail model. The numbers identify the location of several mountains: 1. Pyrenees, 2. Massif Central, 3. Alps, 4. Apennines, and 5. Dinaric Alps. (b) Average linear trends of the annual PHI. Trends with significances below 95% are cross hatched. Note that significant trends were only found for values below −5PHI days (coastDat2, 1951–2010).

(parts of Germany, Poland, Czech Republic, and Slovakia) and south thereof (Slovenia). Note that all significant trends exhibit a negative sign with values below −5 days over the entire 60 year period.

The time series of the PHI (Figure 3) for six representative regions distributed over the whole investigation area show high annual and multiannual variability. For example, around Milan in northern Italy, where the convective potential is highest according to our analysis, mean PHI values range between 18 and 60 days

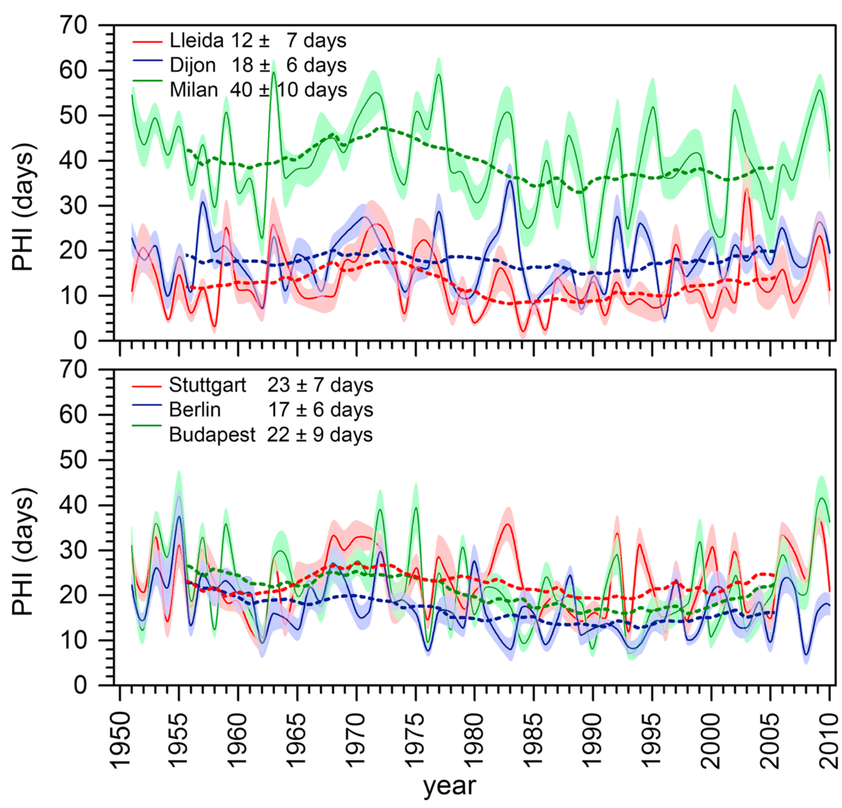

Figure 3. Time series of the annual PHI (mean (solid) ± standard deviation (shaded)), including the 11 year moving average (dashed) for the six different locations (3×3 grid points): around Lleida (Spain), Dijon (France), Milan (Italy), Stuttgart (Germany), Berlin (Germany), and Budapest (Hungary); the locations are indicated in Figure 2a.

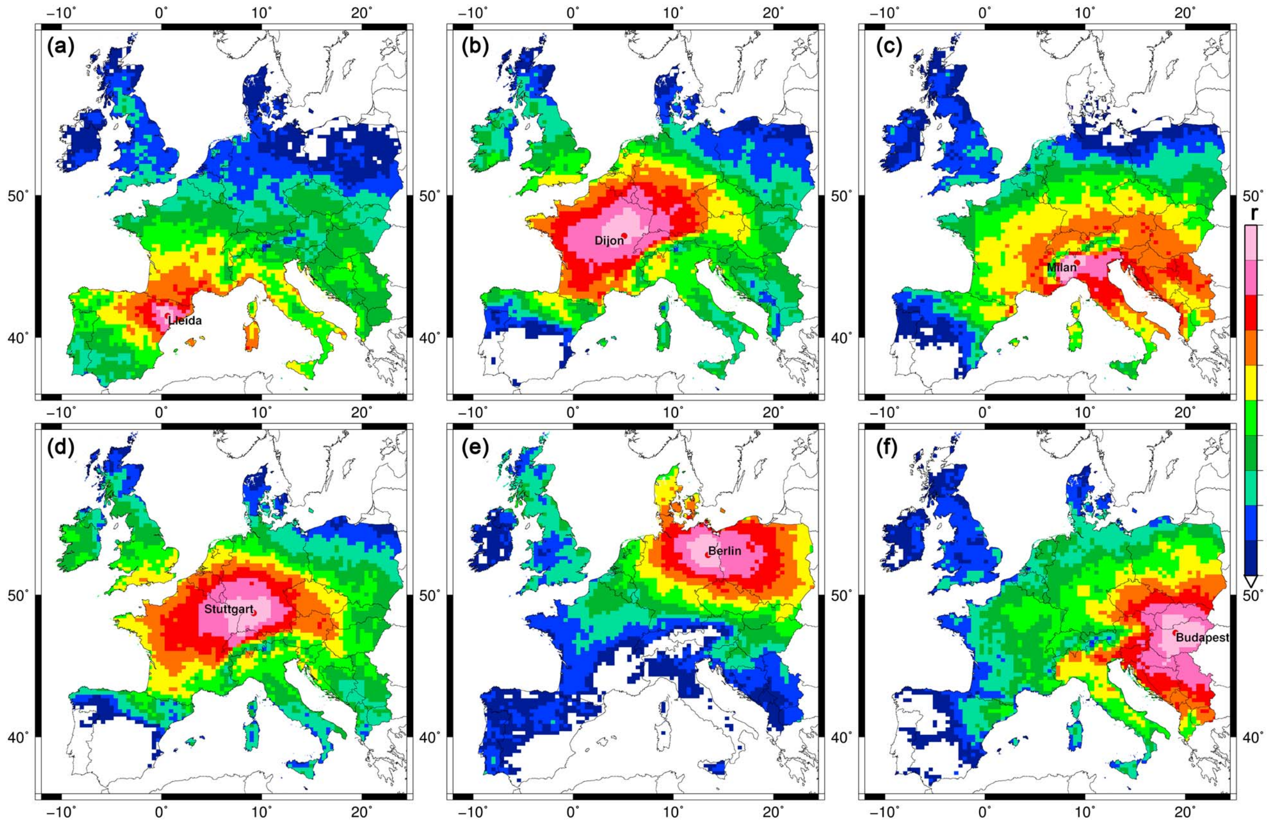

Figure 4. Correlation coefficient between the annual PHI at six different locations (3×3 grid points) and the other grid points.

(upper solid green curve). At all locations, the variability is dominated by periodicities between 1 and 4 years. However, a power spectral analysis based on a fast Fourier transform algorithm did not reveal any periodicity in the time series (not shown). Interestingly, several of the peaks are correlated among most of the locations (e.g., 1955, 1957, 1963, 1977, 1992, and 2009). This finding implies that annual changes in the hail potential are related to larger-scale mechanisms that affect larger areas across Europe. The internal modLHM uncertainty—expressed by the standard deviation of the annual values from the 11 models (shaded in Figure 3)—is comparatively small and supports the above statements. The 11 year moving averages of each station (solid lines in Figure 3) suggest that the hail potential around the 1970s was on average higher than that of the 1980s and 1990s and for some stations at approximately the same level compared with recent years (except for Milan). Note that the high temporal variability apparent for all locations is the main reason for the lack of statistical significance of the linear trends found at most grid points in Figure 2b.

Considering the main drivers for the temporal variability of PHI, the highest relation is found between the time series of PHI and SLI, yielding a Spearman rank correlation coefficient of $r = -0.78$ (not shown). In contrast, the correlation coefficients for the two temperature time series are substantially lower, as already indicated by the lower β_n coefficients. This implies that the annual variability of the PHI is more related to atmospheric stability rather than to near-surface properties.

To examine how representative the six selected time series are, we correlated their annual PHI values with those of all grid points in the investigation area (Figure 4). Around the indicated locations, the Spearman rank correlation coefficients r are very high. The correlation length for $r \geq 0.9$, i.e., the distance where r drops below 0.9, is around 100–150 km in most cases, and it is more than 500 km for $r \geq 0.7$ (except of Lleida). This means that the temporal variability of the hail potential expressed by the time series of PHI is representative for large areas, for example, in the case of Dijon (Figure 4b) being representative of almost the whole of France.

6. Discussion

The fundamental difficulty when relating severe convective weather phenomena such as hail with appropriate meteorological parameters or a combination thereof is the lack of comprehensive, high-quality observations. Even if various studies are available that estimate hail frequency for specific regions, no or only scarce information is available for a larger area such as all of Europe. Furthermore, these regional studies refer to a wide range of spatial scales and consider different time periods, hailstone diameters, or data sets in terms of station data, eyewitness reports, insurance losses, or radar reflectivity (H. J. Punge and M. Kunz, Hail observations and hail frequency across Europe: A review, submitted to *Atmospheric Research*, 2015). These constraints hamper not only a direct comparison of hail hazards among regions but also a thorough evaluation of the results obtained from proxy data such as the PHI. In the following, we attempt to compare our results with the assessments provided by regional studies, but only in a qualitative way. By doing so, we implicitly verify our initial hypothesis that the modLHM tested and adjusted for a limited region in southwest Germany is a suitable way to estimate the hail potential of a large region such as Europe.

Only a few studies have undertaken efforts to estimate hail frequency on a European scale based on data from remote sensing instruments such as satellite, radar, or lightning detectors. The investigations of *Bedka* [2011], for example, based on overshooting tops from satellite infrared brightness temperature, estimate the highest frequency of severe convection around the Alps and over northeastern Spain and the Czech Republic. Both studies of *Punge et al.* [2014] using the same data set and of *Anderson and Klugmann* [2014] based on lightning found reduced convective activity near Atlantic coasts and over northern regions but enhanced activity over Central Europe — especially over the prealpine regions north and south of the Alps — and the eastern parts. Overall, the PHI results are consistent with those continental-scale assessments.

The most striking of our results is the maximum of PHI on the southern side of the Alps. From various studies [e.g., *Morgan*, 1973; *Giaiotti et al.*, 2003; *Manzato*, 2012; *Baldi et al.*, 2014] it is well known that this region is one of the most hail-exposed areas in Europe. In contrast, the increased hail probability estimated by *Baldi et al.* [2014] especially for southern Italy is not reproduced by the PHI. However, their methods based on linear regressions of different proxies (meteorological observations, hailstorm reports, and NCEP/NCAR reanalysis) are not comprehensible and the reliability of the results are not verified. In France, the large-scale gradient from northwest to southeast was also detected by other studies, for example, by *Vinet* [2001] or *Fluck et al.* [2015].

In line with our results for Switzerland are the main findings of *Stucki and Egli* [2007] and *Nisi et al.* [2014] based on radar data and lightning detections, respectively. The authors estimated lowest convective activity over the highest peaks of the Alps, particularly in the Cantons of Valais and Graubünden, and increased activity over the Jura and the prealpine regions north and south of the Alps. The study by *Svabik et al.* [2013] considering a combination of hail reports and radar data confirms the elevated hail potential found in our estimate for upper Austria. The authors also identified a second hot spot with a similar intensity in Eastern Styria, which, however, is not reproduced in our analysis.

The hail potential over the western parts, especially over Great Britain and the Iberian Peninsula, is substantially underestimated by the modLHM. Only over the lower Ebro valley does the model quantify higher PHI values in accordance to several observational studies [e.g., *Sánchez et al.*, 2003; *Ceperuelo Mallafré et al.*, 2009; *García-Ortega et al.*, 2011]. For other regions in Spain, such as the Valencia province [*Saa Requejo et al.*, 2011], or the eastern flanks of the Iberian highlands, where an increased hail hazard is observed, the modLHM does not produce reliable results.

A plausible explanation for these larger discrepancies may be the climate and proximity to the Atlantic, resulting in enhanced static stability and, thus, lower SLI. Especially over Great Britain, SLI is positive in the mean, yielding a negative regression coefficient (see section 3) and giving rise to very low PHI values. Frontal systems and related convective disturbances, on the other hand, which occur preferably in the north, are not considered in the modLHM. Over the Iberian Peninsula, a similar effect may also be decisive. Here the combination of a higher stability stratification of the atmosphere and very high T_{2m} values gives rise to smaller estimates of the PHIs. Since the model and the considered parameters were adjusted to the prevailing climatological conditions in Germany, the model is not able to provide reliable results in those areas. Thus, the application of the model should be restricted to regions with similar conditions to those used for the estimation of the β values such as the central continental part of Europe.

Note, however, that hail is reported to occur also in spring and autumn in countries or areas that are strongly influenced by the Atlantic or the Mediterranean [e.g., *Vinet*, 2001]. Thus, by considering only the peak hail months of Central Europe (June to August), several hail-favoring situations outside of this period may be missed.

Despite the local-scale nature of convective storms, the ambient conditions that favor these weather systems are controlled by large-scale circulation patterns and mechanisms. This finding is suggested by the high correlation length of several hundred kilometers for the annual variability of the PHI among different sites. This means not only that the temporal variability of the time series of PHI is representative for areas of mesoscale sizes but also that large-scale mechanisms such as natural variability of the climate system or teleconnections may explain the large annual and multiannual variability of convective probability. Such relations have been observed by some other authors. For example, *Sutton and Hodson* [2005] found that changes in the Atlantic Ocean are an important driver of the multidecadal variations in summer precipitation over Western Europe. For the Unites States, a recent study by *Allen et al.* [2015] provided evidence that El Niño–Southern Oscillation events modulate tornado and hail occurrences during the winter and spring by altering the large-scale environment.

7. Summary and Conclusions

Based on the logistic hail model developed by *Mohr et al.* [2015], we have presented a modified version that enables an assessment of the hail potential across Europe. The model is based on the Lifted Index and minimum and maximum temperatures. The main objectives of our study were to estimate the convective potential associated with hail across Europe, to assess spatial differences, to verify the results in a qualitative way with other published studies, and to examine long-term temporal variability. For those purposes, the adjusted logistic hail model modLHM was applied to a regional retrospective analysis (coastDat2) driven with NCEP/NCAR1 over a 60 year period (1951–2010).

The following major findings and conclusions are inferred from the obtained results:

1. The logistic hail model used in this study provides reliable results in terms of number of days with an increased probability for severe hail. The modLHM, tested and adjusted for a limited region in southwest Germany, can be applied to estimate the hail potential of a large region.
2. The model results generally agree with prevailing European-scale and regional-scale studies on hail frequency. However, the application of the model is restricted to regions with similar prevailing climate conditions as those of the calibration region.
3. Over the past 60 years, the hail potential shows large annual and multiannual variability. The trends are mostly positive in the western parts and negative to the east. However, due to the large temporal variability, the trends are not significant at most of the grid points.
4. The hail potential estimated by PHI is not a local-scale property; rather, it is valid for mesoscale regions. This finding suggests that despite the local-scale nature of convection, the ambient conditions which favor these events are mainly controlled by large-scale circulation patterns and mechanisms.

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