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# Hail frequency estimation across Europe based on a combination of overshooting top detections and the ERA-INTERIM reanalysis

H.J. Punge[a,c,*], K.M. Bedka[b], M. Kunz[a,c], A. Reinbold[a]

[a] Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute of Technology, Karlsruhe, Germany
[b] NASA Langley Research Center, Hampton, Virginia, USA
[c] Center for Disaster Management and Risk Reduction Technology (CEDIM), Karlsruhe Institute of Technology, Karlsruhe, Germany

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ABSTRACT

This article presents a hail frequency estimation based on the detection of cold overshooting cloud tops (OTs) from the Meteosat Second Generation (MSG) operational weather satellites, in combination with a hail-specific filter derived from the ERA-INTERIM reanalysis. This filter has been designed based on the atmospheric properties in the vicinity of hail reports registered in the European Severe Weather Database (ESWD). These include Convective Available Potential Energy (CAPE), 0–6-km bulk wind shear and freezing level height, evaluated at the nearest time step and interpolated from the reanalysis grid to the location of the hail report. Regions highly exposed to hail events include Northern Italy, followed by South-Eastern Austria and Eastern Spain. Pronounced hail frequency is also found in large parts of Eastern Europe, around the Alps, the Czech Republic, Southern Germany, Southern and Eastern France, and in the Iberic and Apennine mountain ranges.

## 1. Introduction

Hailstorms frequently cause large material damage to buildings, infrastructures, or crops in many parts of Europe. However, the spatial distribution of hail hazard across Europe is not yet well understood (Punge and Kunz, 2016). Ground-based observing networks for hail such as hailpad stations cover only small areas, and insurance damage data, also limited in coverage, is affected by variable exposure, vulnerability, and other factors. Radar-based studies of hailstorm or severe thunderstorm frequency are limited to the coverage provided by the respective national weather services networks used (Puskeiler et al., 2016; Junghänel et al., 2016; Nisi et al., 2016; Skripniková and Řezáčová, 2014; Kaltenböck and Steinheimer, 2015; Seres and Horváth, 2015; Goudenhoofdt and Delobbe, 2013). Visibility gaps exist due to limited range of the radar devices topographic obstacles. In addition, the use of various radar devices with different frequency bands makes calibration very difficult, in particular when the focus is on rare extreme events such as hailstorms.

Hence a hail-specific observing system spanning the entire continent is still nonexistent. This has led to the development of satellite derived products (Cecil and Blankenship, 2012; Merino et al., 2014; Punge et al., 2014) for hailstorm identification and hazard estimation. In particular, convective overshooting at cloud tops (overshooting tops, OTs) observed by geostationary satellites indicates strong convective updrafts capable of producing severe hail (Bedka, 2011; Punge et al., 2014; Proud, 2015). The prevalence of OTs in hailstorm environments has been shown by Bedka (2011), but the reverse remains difficult to prove due to the lack of complete and homogeneous ground observations of hail.

Previous studies by Merino et al. (2014) and Melcón et al. (2016) have used satellite observations and derived products to identify likely hail-producing storms. These approaches have utilized a combination of visible and near-IR reflectance and longwave IR water vapor absorption channel brightness temperatures. These authors found that cold, optically thick ice cloud composed of small ice crystals were most likely to produce hail over southwest France and Spain. Cold thick cloud and small ice are proxies for strong updrafts where hail growth occurs within convective storms. This combination of parameters could also be present in wind- or tornado-producing storms. Their "Hail Detection Tool" is a daytime only product because reflected sunlight is required but is shown to perform quite well for discriminating hail- from hail-free storms. Nevertheless, reflected sunlight can be challenging to use within automated severe convective storm detection algorithms. Shadows at high solar zenith angles caused by vertical perturbations in convective cloud tops such as gravity waves and OTs common in hail-producing storms will reduce reflectance and perhaps inhibit detection within their approach. Biases can also arise near the day-night terminator. In contrast, the Bedka (2011) approach described in this paper is

* Corresponding author.
*E-mail address:* punge@kit.edu (H.J. Punge).

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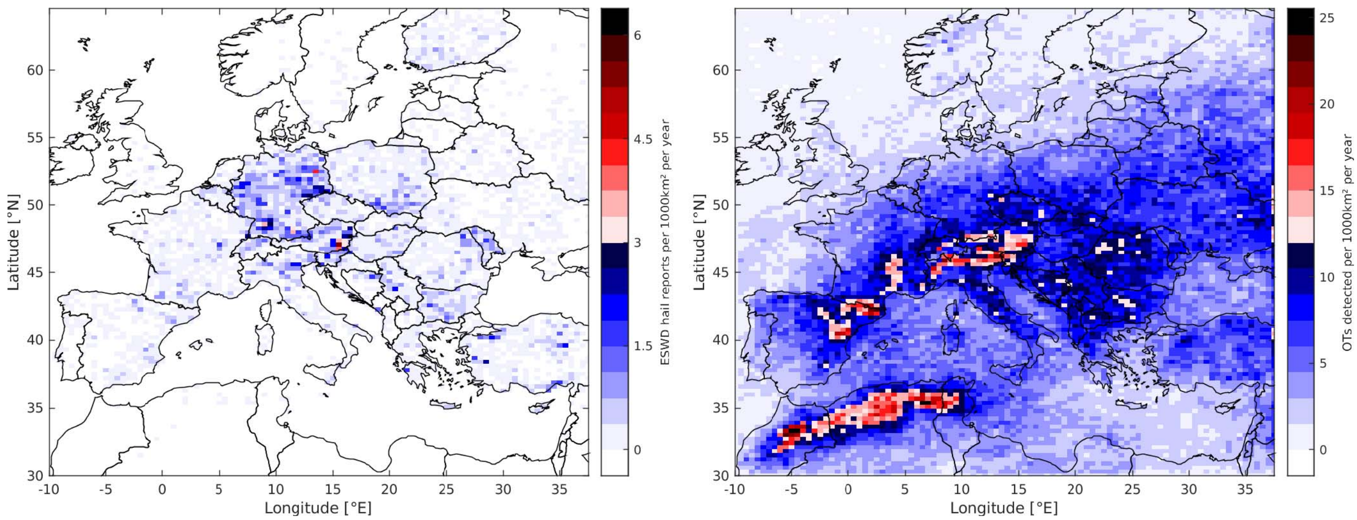


**Fig. 1.** Number of hail reports in the ESWD database (left) and overshooting cloud top detections (right) per grid cell, on a $0.3^{\circ} \times 0.5^{\circ}$ grid, in the period 2004–2014.

day-night independent but is based on a similar premise as Merino et al. (2014) and Melcón et al. (2016) where we try to identify strong updraft regions within convective anvils using spatial analyses of IR brightness temperatures coupled with numerical model tropopause information.

There are two sources of uncertainty regarding the OTs. Firstly, not all OT detections are correct. Cloud top patterns can look like OTs, but in reality they are not: Decayed updraft from a recent OT will produce cold clouds that are advected downstream and could resemble an OT. Second, not all severe thunderstorms that generate OTs produce hail on the ground. This is the case when conditions in the atmosphere do not favor hail formation in a thunderstorm or cause hail to melt before it reaches the ground, e.g., due to a very high freezing level. Even correct OT detections are therefore an imperfect indicator for hail on the ground.

The principal objective of this article is to reduce these uncertainties by filtering OTs based on the likelihood of hail and thereby improve on the hail frequency estimation presented in Punge et al. (2014). That study used a simple OT temperature threshold and does not take ambient conditions into account. Through the combination with an independent dataset, the uncertainty on the estimated hail frequency can be reduced, in particular in regions with frequent OTs but little evidence for hail on the ground. This is a prerequisite for the application of the OT-based approach to other regions of the world. For example the Maghreb region of northern Africa, which features very high OT counts, had been omitted in the previous work because of this uncertainty. Other objectives are to 1) investigate the resulting hail frequency distribution at higher spatial resolution, 2) discuss the distribution in context with topography, and 3) compare with previous, regional scale studies of hail frequency. To achieve these goals, we compare atmospheric parameters in the environments of hail reports and OT detections.

One may assume that satellite-derived parameters alone could be used to discriminate hail from non-hail producing storms. In reality, hailstorms can appear quite similar to severe wind and tornado producing storms in IR satellite imagery. In addition, we cannot develop robust relationships between satellite observations and hail occurrence or hail size due to uncertainties in the reported spatial locations of storms and their exact time of occurrence, coupled with the relatively coarse 15-min MSG satellite imaging frequency.

The atmospheric conditions in the environments of individual intense thunderstorms and hailstorms in particular in Europe have been analyzed in numerous studies (e.g., Groenemeijer and van Delden, 2007; Kunz, 2007; Sánchez et al., 2009; Palencia et al., 2010; Mohr and Kunz, 2013; Tudurí and Ramis, 1997; Eccel et al., 2012; García-Ortega et al., 2011; Gascón et al., 2015). Convective parameters based on the thermal and humidity profile of the atmosphere have been used to describe the likelihood of extreme thunderstorm development (Kunz, 2007; Mohr and Kunz, 2013). A number of studies, in particular for North America, found vertical wind shear to be an essential ingredient for the development of supercells and bow echoes, and thus high probability of hail fall and tornadoes (e.g., Markowski and Richardson, 2010).

Atmospheric parameters associated with the presence of convection, such as Convective Available Potential Energy (CAPE) can help identify where hail producing storms could occur (Brooks et al., 2003; Allen et al., 2015). Products and indices based on such atmospheric variables are particularly useful for long-term studies of climatic variability in the past and future (Mohr et al., 2015; Tippett et al., 2015). However, the complex topography in Europe plays an important role in storm initiation and the distribution of hail hazard (Počakal et al., 2009; Kunz and Puskeiler, 2010; Davini et al., 2011; Burcea et al., 2016). For purposes like risk modeling for private industry, it is necessary to know where hail events could have occurred, and hence actual observations of storms such as provided by satellite or radar are indispensable.

Therefore, we chose the following approach to quantify hail hazard OTs. We evaluate atmospheric conditions in the vicinity of reported hailstorms in the ERA-INTERIM reanalysis, and then compare to conditions found in OT environments (Sections 2.1–2.3). A filter method is used to identify hail-prone OTs (Section 2.3). A climatology of the filtered OT dataset is then presented (in Section 3) and discussed in the context of orography and existing literature (Section 4).

## 2. Data sets and methods

### 2.1. Hail reports in ESWD

The European Severe Weather Database (ESWD Dotzek et al., 2009), provided and maintained by the European Severe Storms Laboratory (ESSL), is the only multinational database and is by far the biggest archive for hail reports in Europe. Population density, technological innovation such as increasing high speed internet availability, and increasing public awareness of extreme meteorological events led to a rapid increase in ESWD reports in recent years. The resulting large inhomogeneity of the reports over time and space, notably an observation bias towards urban centers (see Fig. 1a), hampers their use for hail probability assessment. However, these reports form the only data set available that provides reliable information about hail, including maximum size of stones, for broad geographic areas. In total, 12, 282