An ERA-Interim HAILCAST hail climatology for southern Africa

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Abstract

Understanding the character of hail is an important part of mitigating its impact on life and property. Climatologies of hail over South Africa are rare and based on observed data with a coarse spatial and temporal resolution. In this paper, a hail climatology is created for southern Africa from reanalysis data. Pseudo-soundings are produced from ERA-Interim data and the HAILCAST model, which predicts the diameter of hail, is run using these soundings from 1979 to 2017 at six-hourly intervals. The hail day frequency of the ERA-Interim HAILCAST (EIH) climatology compares well to historical climatologies, although the horizontal resolution of ERA-Interim makes it difficult to pinpoint the exact location of hail in areas of steep topography. Furthermore, the EIH climatology tends to over-predict hail with diameters greater than 3 cm. Detail that was previously unavailable, such as the seasonal and temporal distribution of hail over the entire South Africa, is now available from the EIH climatology. The frequency of hail over the winter rainfall area and over countries bordering South Africa is estimated for the first time. It is recommended that the procedure is repeated with numerical weather prediction models with a higher resolution to determine whether the increased resolution will more accurately identify areas of hail.

Keywords: Hail, climatology, ERA-Interim, HAILCAST, southern Africa.

1. Introduction

Owing to the lack of in-situ observations, the frequency of occurrence and the spatiotemporal distribution of hail in South Africa – especially large, damaging hail – is largely unknown. The official source of hail information is the South African Weather Service (SAWS). A few manned SAWS stations report hail if it occurs at a station close to the time of observation, the only size criteria required from the SAWS database is that the hail was greater than 5 mm in diameter. The SAWS weather stations do not have hail observation devices, and the distribution of the manned stations is coarse, making the recording of events unreliable. Nevertheless, damaging hail events in South Africa occur from time to time, mainly over the large metropolitan areas of South Africa and particularly over the Highveld (Simpson and Dyson, 2018). In November 2013, two major hailstorms occurred over Gauteng (see Figure 1), which cost the insurance industry ZAR 2 billion (± US$ 160 million). The hailstorm of 28 November 2013 “was the single worst insurance event in South Africa’s history” (PwC as cited in Risk Africa Magazine, 2015). The South African Highveld is the elevated area in the eastern interior that has an altitude of 1 500 m above sea level (ASL); some of the ridges on the Witwatersrand are as high as 1 700 m (see Figure 1).

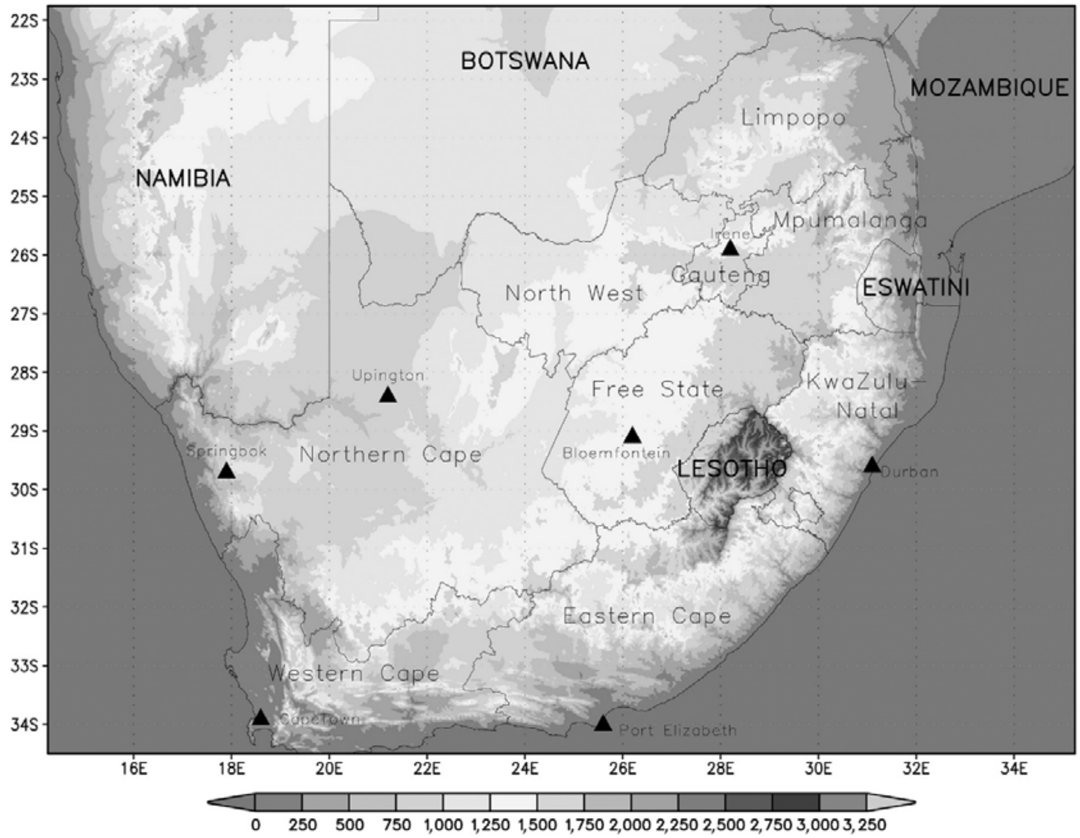

Figure 1. Location and a topographical map of southern Africa. The locations where upper air ascents are done are indicated by triangles

The lack of reliable hail observations is a global issue. Australia has a poor observational record of severe weather, including large damaging hail. (Allen and Karoly, 2014). Punge and Kunz (2016) describe how hailstorms in Europe are inaccurately recorded due to a lack of observation systems. Some European regions have hailpad networks with the main purpose of understanding the efficacy of hail suppression activities on hail damage to crops. A hailpad is an apparatus that measures the size distribution and mass of hailstones. In the USA, Storm Data is an observational hail record that is maintained by the National Climatic Data Center. It currently contains data from January 1950 to October 2019 and consists of data from emergency managers, spotters, damage surveys, newspaper reports, insurers and the general public, among others (NOAA, 2020). However, there are some reporting biases in Storm Data because non-severe hail events are under-reported and population density heavily influences reports (Allen et al., 2015, Cintineo et al., 2012). There is scepticism about the usefulness of Storm Data to provide an accurate climatology of maximum hail size distribution (Blair et al., 2017) as numerous non-meteorological factors play a role in the data set (Allen and Tippett, 2015). One such a factor is the large number of hail size reports in Storm Data which are estimated rather than measured (Jewell and Brimelow, 2009). Another important observational database is from the Alberta Hail Project in Canada which lasted from 1957 to 1985 and covered 33 700 km^2, and around 20 000 farmers reported maximum hail size and other hail characteristics (Brimelow et al., 2002).

Despite the lack of observational hail data, there is a dire need to understand the spatiotemporal character of hail. Hail climatologies help identify where improvements are needed to understand the atmospheric conditions that lead to hail. Determining hail risk from climatologies is important to insurers and economists. Farmers can make informed decisions about the threat of hail if long-term hail data is available (Punge and Kunz, 2016).

In recent years, several attempts have been made to create hail or severe thunderstorm climatologies using reanalysis data. In the 2000s, Brooks et al. (2003, 2007) started using reanalysis data to determine the characteristics of severe thunderstorms globally. A general approach is to compare hail observations with the parameters that are available from reanalysis data. The appropriate parameters are then used to create the climatologies. Examples include Eccel et al. (2012), who integrated hailpad observations and instability parameters from the ERA40 data to create a hail climatology for the Alps. Allen and Karoly (2014) used the same approach for Australia, and Burcea et al. (2016) used this methodology for Romania. In South Africa, Blamey et al. (2017) used Convective Available Potential Energy (CAPE) and deep layer wind shear to identify favourable environments for severe storms. In an additional study in Europe, Punge et al. (2017) estimated hail frequency by combining the detection of overshooting tops from Meteosat Second Generation (MSG) satellites with convective parameters in ERA-Interim. Hand and Cappelluti (2011) developed a global hail climatology using the convection diagnosis procedure in the Unified Model. Prein and Holland (2018) identified predictors in ERA-Interim reanalysis and developed a hail algorithm that was used over several temporal and spatial scales. They demonstrated its usefulness to predict hail frequencies and the annual cycle of large hail over conterminous United States (CONUS), Australia and Europe. Allen et al. (2015) used monthly averages of several parameters from the North American Regional Reanalysis (NARR) dataset to determine the predictability of hail in CONUS from monthly averaged datasets.

Climatologies created from reanalysis data are particularly valuable as the reanalysis data extends over a lengthy period and have continuous records. However, the empirical relationships between severe storms and instability parameters may only hold for the region for which they were developed and may not hold in a future climate (Brimelow et al., 2017). These climatologies are very useful to identify favoured areas for the development of severe storms and hail but lack information on the geographical distribution of hail size. In this paper, the HAILCAST model (Brimelow et al., 2002) was run from 1979 to 2017 using ERA-Interim proximity soundings over South Africa to create a hail climatology. The research in this paper is distinguished from previous South African climatologies (Held, 1974, Carte and Held, 1978) as HAILCAST provides an estimation of hail size. Although it is still a proxy of reality, it provides more detail than the empirically-derived climatologies that are available from using atmospheric parameters alone, because HAILCAST simulates the growth of hail from first principles. One of the advantages of using Era-Interim reanalysis data to compile a climatology is that a continuous record is available and the results are not influenced by non-meteorological factors such as population density or observation methods. The results discussed in this paper mainly focus on South Africa, although results for some on the neighbouring countries are also included.

This paper is structured as follows: Section 2 provides detail on the ERA-Interim reanalysis and HAILCAST model. In Section 3, the performance of HAILCAST is shown during November 2013, and in Section 4, a comparison is made between HAILCAST and previously observed hail climatologies. Section 5 shows the temporal and spatial distribution of hail over southern Africa, while Section 6 provides a discussion of the results and recommends future research. In Appendix S1, information is provided about the verification of the ERA-Interim pseudo soundings against the Irene sounding over the Highveld of South Africa.

2. Data and methodology

2.1 ERA-Interim reanalysis

The ERA-Interim reanalysis (Dee et al., 2011) from the European Centre of Medium-Range Weather Forecast (ECMWF) was used to create pseudo-proximity soundings over South Africa. The dataset has a horizontal resolution of 0.75° with 29 vertical levels from 1 000 hPa to 50 hPa. An additional 30th level is surface data with the temperature and dew point temperature at 2 m above ground level (AGL) and zonal and meridional winds at 10 m AGL. The ERA-Interm grid boxes vary in size from about 5800 km^2 in the south to 6400 km^2 in the north of the domain. The temperature, dew point temperature, geopotential height, as well as wind direction and speed on all levels at every grid point, were isolated over South Africa for 0000, 0600, 1200 and 1800 UTC for every day from 1979 to 2017. The interior of South Africa is characterised by an elevated plateau that rises to higher than 1 500 m ASL over large areas resulting in a surface pressure close to 850 hPa. Pressure levels lower than the surface pressure were used to create the soundings over the entire domain.

One of the major constraints in the ERA-Interim dataset is that the horizontal resolution of 0.75° requires the use of convective and boundary layer parametrisation schemes. This may result in inaccurate vertical profiles of temperature and dew point temperature (Taszarek et al., 2018). Convective parametrisation schemes are not developed to represent single convective storms (Sanderson et al., 2015) and the number and intensity of convective storms may, therefore, be inaccurately captured by the reanalysis dataset. Consequently, there will be spatial and temporal differences between observed and modelled hail climatologies. Another limitation in the creation of the pseudo-soundings is that the horizontal resolution of the ERA-Interim data in areas with significant variation in topography may result in soundings that do not accurately represent the spatial variability of an area.

Generally, a drawback of reanalysis data is that strong vertical gradients are not well represented (Brooks et al., 2003, Allen and Karoly, 2014). This is of particular concern when simulating severe storm soundings as the thermal (capping) inversion could be misrepresented. Despite these limitations, Taszarek et al. (2018) found that moisture variables, as well as temperature lapse rates, compare well to observed soundings over Europe in the ERA-Interim dataset. Taszarek et al. (2018) identified inaccuracies in instability parameters such as CAPE and suggest that, qualitatively, climatological results are robust, but there may be quantifiable differences in threshold values of parameters compared to the observed soundings.

2.2 HAILCAST

HAILCAST is the combination of a steady-state cloud model and time-dependent hail growth model that predicts a maximum hail diameter. HAILCAST was initially developed by Poolman (1992) for application in South Africa and later further modified by Brimelow et al. (2002) and applied in Canada and the USA (Jewell and Brimelow, 2009) using observed soundings. Brimelow et al. (2006) implemented HAILCAST on an operational Numerical Weather Prediction (NWP) model and found that HAILCAST could predict maximum hail size over western Canada using prognostic model soundings, but this approach had limited success in accurately predicting the location of hailstorms. In recent years, HAILCAST has been more extensively used in conjunction with NWP output. HAILCAST is a diagnostic in the Weather Research and Forecasting (WRF) model (Creighton et al., 2014). Melick et al. (2014) used the HAILCAST diagnostic as part of the 2014 Spring Forecasting Experiment in the USA and found a systematic overestimate of hail size. HAILCAST implemented in WRF was used to predict hail over complex topography in Switzerland (Trefalt et al., 2018).

The 2002 version of HAILCAST (Brimelow et al., 2002) was run using ERA-Interim pseudo-soundings. Thunderstorms are very sensitive to slight changes in surface temperature and moisture (Crook, 1996). Following the method of Brimelow et al. (2006), the uncertainty in the value of surface variables is compensated for by running HAILCAST several times with different input data, which creates an ensemble of forecasts. These forecasts are produced by adding perturbations of +1.0 °C, +0.5 °C, -0.5 °C and -1.0 °C to ERA-Interim surface temperature and dew point temperature at each grid point, and running HAILCAST for all the combinations. Twenty-five individual hail diameter forecasts are created in this way, and the average hail size is the arithmetic mean of the hail sizes of each member of the ensemble, including zeroes.

An ERA-Interim HAILCAST (EIH) hail day is defined as a day when the mean diameter of the ensemble members was greater than 1 cm at any of the four time steps in the model. The hail day frequency (HDF) was calculated for two classes, when the average ensemble hail size was greater than 1 cm (HDF1) and greater than 3 cm (HDF3). Hail with diameters between 1-1.9 cm may cause some damage to vineyards and orchards (Dessens et al., 2007, Morel, 2014, Brown et al., 2015, Rasuly et al., 2015) while hail with diameters larger than 2 cm damage cars, roofs and cause severe damage to plants and crops. The impact speed of 2 cm hail varies between 55-65 kmh^{-1} (Heymsfield et al., 2020). The impact of hail larger than 3 cm is to damage buildings and cars (Rasuly et al., 2015). Hail with diameters greater than 1 cm was chosen in this paper as one of the hail classes as it represents small hail, while hail with diameters larger than 3 cm is associated with significant damage to property.

3. The performance of HAILCAST during November 2013

The verification of the temperatures and winds throughout the troposphere on the ERA-Interim soundings compare very well with those on the Irene sounding (Appendix S1). However, ERA-Interim tends to overestimate the dew point temperatures in the middle and upper troposphere. Even though there appear to be some discrepancies between the observed and modelled sounding at Irene, the following two sections will discuss the performance of the EIH predictions when compared to known severe hail events and observed climatologies.

The lack of hail observations makes it generally difficult to evaluate hail forecasts. Validation, therefore, takes place in areas with dense observation networks or by using case study events and remote sensing platforms such as radar and satellite. Brimelow et al. (2002), Brimelow et al. (2006) and Manzato (2013) used hail observations to evaluate hail forecasts, while

Brimelow et al. (2006) and Blair et al. (2011) employed radar reflectivity data to evaluate hail size estimates. It is common practise to evaluate hail forecasts with case events (Blair et al., 2011, Adams-Selin and Ziegler, 2016, Snook et al., 2016) and in the past decade insurance data have also been used to validate hail forecast (Kunz and Puskeiler, 2010, Morel, 2014, Brown et al., 2015, Kunz and Kugel, 2015). In this section, the predictions made by HAILCAST are compared to hail insurance data for two major hail events in South Africa.

Two hail events over Gauteng (see Figure 1) on 11 and 28 November 2013 cost the insurance industry in South Africa more than ZAR 2 billion (approximately US$ 160 million). Both of these extreme events were caused by supercell thunderstorms (Rae, 2015). The performance of HAILCAST with pseudo-soundings from ERA-Interim datasets is not only shown for these two events, but for the entire month of November 2013 over Gauteng. Insurance claim data was obtained from MMI Holdings and was used to identify the location of hail during the two severe hail days. MMI Holdings has a large number of policyholders in Gauteng, but this number decreases rapidly outside the province's borders. Furthermore, most of the policyholders are located in the metropolitan areas of Johannesburg and Pretoria. The data of MMI Holdings is used to indicate the geographic distribution of hail damage over Gauteng.

The number of hail claims MMI Holdings processed was calculated in the geographic area that is represented by the ERA-Interim grid boxes in Gauteng. The number of hail claims are plotted together with the EIH hail size estimation in Figure 2 for 11 November 2013 (a) and 28 November 2013 (b). On 11 November, the EIH estimated the hail size to be 2 cm in the eastern parts of the province and 1 cm in the west. MMI Holdings processed 159 hail claims in south-eastern Gauteng and only 19 in the north-east. The grid box in the north-west had no hail claims, while the EIH predicted 1 cm diameter hail. One should consider that most of the north-western grid box falls outside the borders of Gauteng where MMI Holdings has fewer policyholders. Furthermore, hail with diameters of 1 cm do not necessarily cause damage to property (Dessens et al., 2007) and this could in part explain the absence of hail claims in this grid box. On 28 November 2013 (Figure 2b), there were 184 hail claims in south-western Gauteng and 86 in the north-east. The EIH estimated the hail size in the north-east to be 1 cm, but there were many more hail claims in comparison with 11 November when EIH predicted 2 cm diameter hail. In the south-west, the EIH forecast hail as large as 5 cm. This corresponds to the substantial number of hail claims (184) that MMI Holdings processed in this area. Furthermore, PwC (as cited in Risk Africa Magazine (2015)) reported that the average hail size on 28 November 2013 was 5 cm.

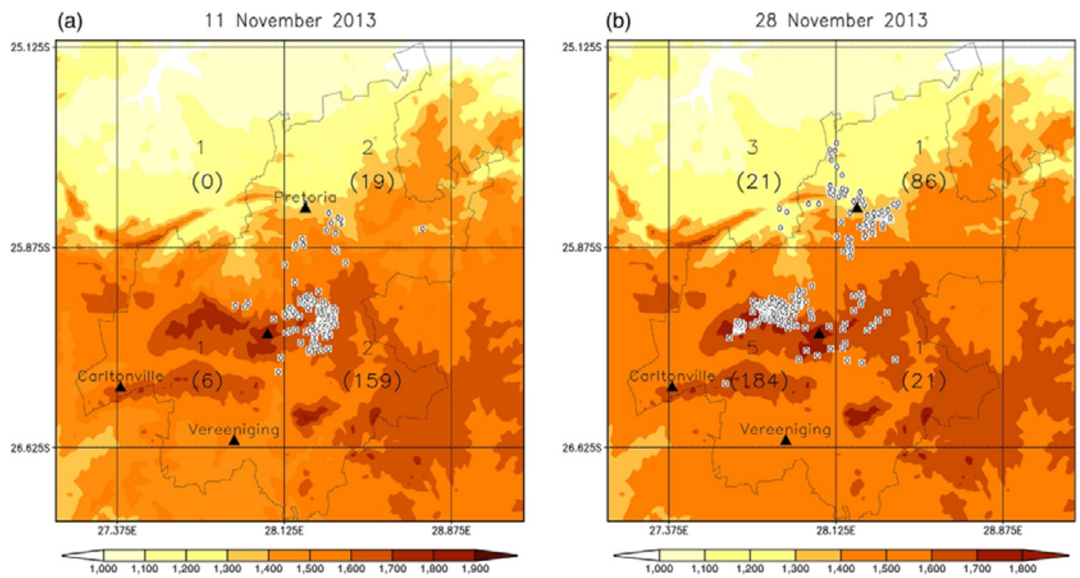

Figure 2. The EIH hail size estimation and the number of MMI holdings hail claims (in brackets) for November 11, 2013 (a) and November 28, 2013 (b) over the four ERA-Interim grid boxes in Gauteng. The location of the hail damage reports is indicated by 'o'

The EIH estimated an additional two days in November 2013 on which the hail diameter could have been more than 3 cm: 20 November 2013 and 24 November 2013. On 20 November, MMI Holdings processed three hail claims in Gauteng. It did not process any hail claims on 24 November. Although these data suggest that EIH overestimates hail size for severe events, we also wish to determine how useful the EIH data are for quantifying the climatological aspects of hail across southern Africa.

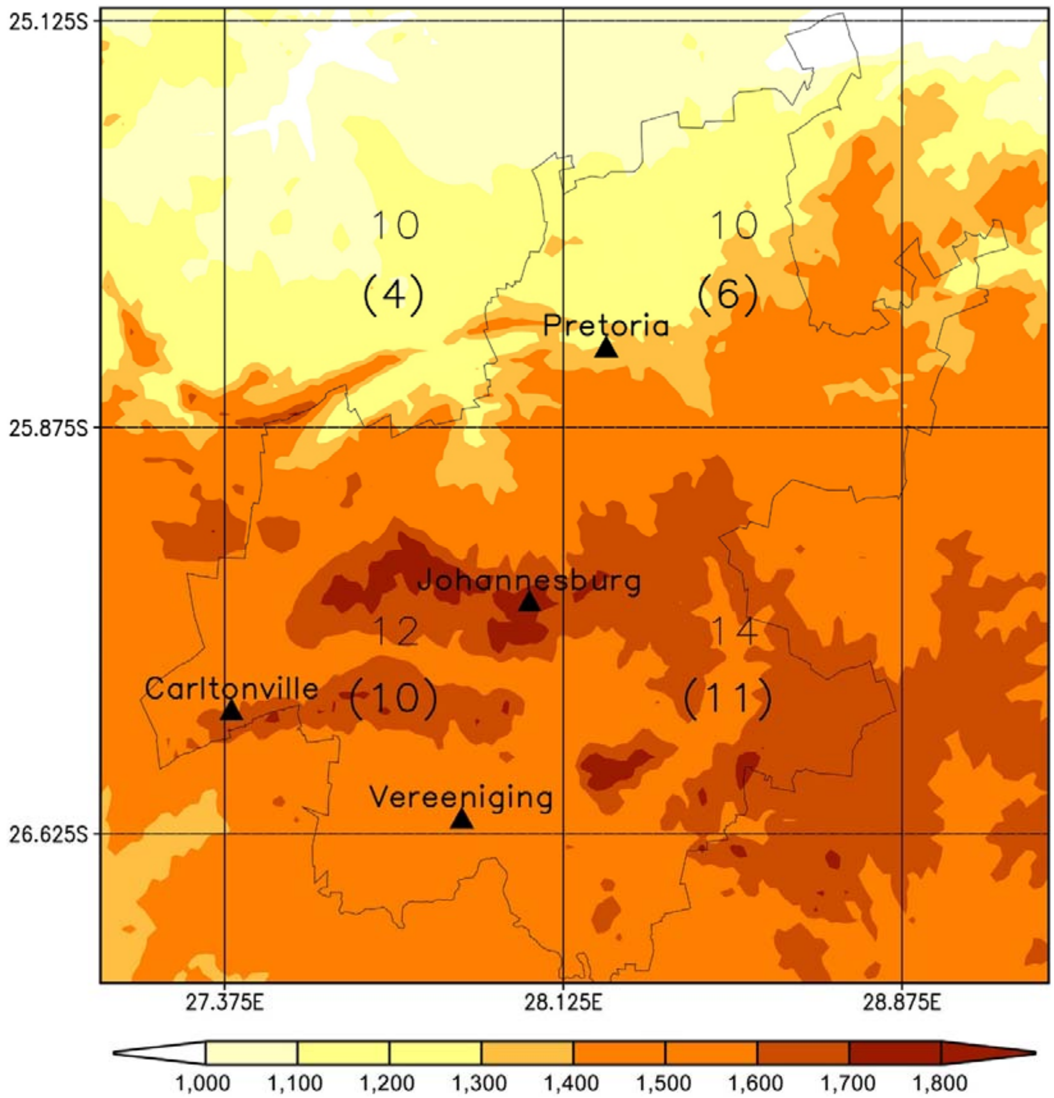

Figure 3. The EIH monthly HDF for hail with diameters greater than 1 cm, as well as the number of MMI holdings hail claim days (in brackets) for November 2013 in the four ERA-Interim grid boxes over Gauteng

In Figure 3, the hail day frequency for hail bigger than 1 cm in diameter for November 2013 is compared to the hail claim day frequency from the MMI Holdings data. A hail claim day is defined as a day when there was at least one hail claim in the geographic area represented by the ERA-Interim grid box. For the entire month of November, the EIH predicted a hail day frequency (HDF) of 10 over northern Gauteng and an HDF of 12 over the south-west (as opposed to 14 over the south-east). Across the entire Gauteng, there were fewer hail claim days than the number of days that EIH predicted hail.

The results indicate that the EIH appears to over-estimates large hail events. Furthermore, the variable topography of the Highveld in Gauteng (Figure 1) emphasises one of the weaknesses of the horizontal resolution of ERA-Interim in areas with significant variation in topography (Taszarek et al., 2018). The horizontal resolution of ERA-Interim necessitates the use of convective parametrisation schemes. These schemes do not resolve the number and intensity of convective storms (Sanderson et al., 2015), therefore spatial and temporal differences can be expected between observed and modelled hail climatologies. The ERA-Interim grid boxes over Gauteng covers an area with a complex topography (Figure 3). Consider the south-eastern grid box where the altitude changes from 1400 m in the south to over 1700 m in the Witwatersrand (blue shades). The properties of a convective storm will change as it moves over the geographical area represented by this grid box. A single grid point is not truly representative of the variation in topography within that grid box. Note in Figure 2 how the majority of the hail claims was over the elevated area of the Witwatersrand. Held (1974) and Carte and Held (1978) described the good correlation between increasing topography and hail days over the Witwatersrand.

The EIH climatology will henceforth be compared to previous climatologies complied from observations in South Africa to determine its usefulness.

4. A comparison between the HAILCAST climatology and observed hail climatologies in South Africa

The sub-tropical high-pressure belt dominates the climate of South Africa. This high is split in two over the continent in summer when a heat low develops over the central interior of South Africa, and provided abundant moisture; thunderstorms develop east of the low. The largest part of South Africa receives rainfall in summer (October to March) from convection (Gijben, 2012). The convection is initiated by organized synoptic and mesoscale weather systems or may be heat generated. Some of the synoptic and mesoscale weather systems include Tropical Temperate Troughs (Hart et al., 2013), Cut-off lows (Singleton and Reason, 2007), Continental tropical lows (Webster, 2019), Mesoscale Convective Systems (Blamey and Reason, 2012) and supercells (Rae, 2015). The southwestern parts of South Africa (see Figure 1) receives winter rainfall from extra-tropical weather systems, such as cold fronts or cut-off lows (Taljaard, 1996) and has a very low frequency of lightning (Gijben, 2012). The south and southeast coast and adjacent interior receive rainfall all year round (Engelbrecht et al., 2015). Most thunderstorms (and therefore also hail) occur in the eastern part of South Africa with only a few thunderstorms (and associated hail) days in the south-west.

There are a few notable historical observational hail climatologies for the South African region. Once such climatology is from Le Roux and Olivier (1996), cited in Schulze (2001), who created a point hail day frequency map of South Africa (see Figure 4). This map was compiled from 113 manned SAWS synoptic weather stations over the summer rainfall area for the period 1960 to 1986. This climatology is very similar to that of Schulze (1965) who created a hail climatology with data from 1950-1964. In the Le Roux and Olivier climatology, the highest point frequency of hail per annum occurs over Lesotho (more than seven days) with between three and five days over the Highveld. The map in Figure 4 represents the observed frequency of hail (diameter greater than 5mm) at a point location.

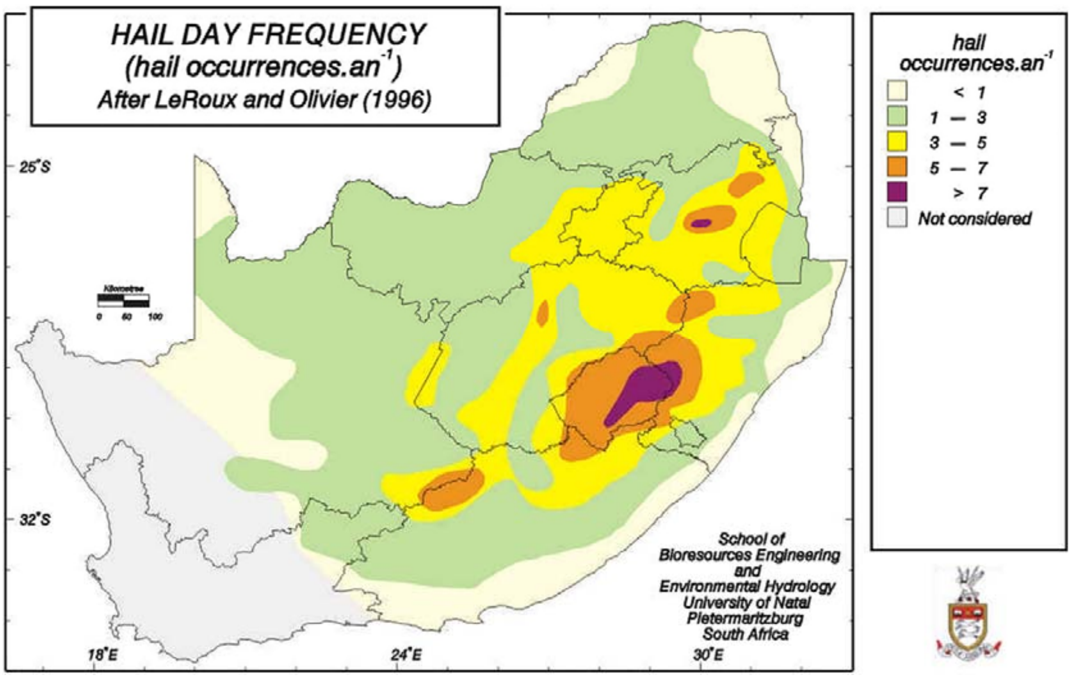

Figure 4. The annual observed point HDF over the summer rainfall area of South Africa between 1960 and 1986 for hail with diameters greater than 0.5 cm (Le Roux and Olivier, 1996, cited in Schulze, 2001)

Olivier (1990) created a point climatology of hail in north-eastern South Africa in the former province of Transvaal. This province comprised the present provinces of Mpumalanga, Gauteng, Limpopo and the eastern part of North West province (see Figure 1). Olivier (1990) obtained hail data from manned SAWS stations between 1962 and 1986 and used 66 stations in the analysis. This dataset was supplemented by media reports and insurance claims. Results of the study of Olivier (1990) show that the highest point hail day frequency occurred over the Highveld of Mpumalanga. In the four north-eastern provinces, the hail season is mostly confined to austral summer (October to March), peaking in November. Hail usually occurs between 1000 UTC (1200 LT) and 1800 UTC (2000 LT), with the highest occurrence between 1500 UTC (1700 LT) and 1600 UTC (1800 LT) (Olivier, 1990).

There is an overlapping period of six years during which results are available from Olivier (1990) and the EIH climatology (1979/80 to 1984/85). Olivier (1990) determined a hail day frequency over homogeneous areas of the former Transvaal. One of the areas includes Gauteng and the eastern parts of North West province. A similar geographic area was identified in the EIH data and the total number of hail days in this area (with hail larger than 1 cm) per year (July to June) was determined. The comparison between the two datasets is shown in Figure 5.

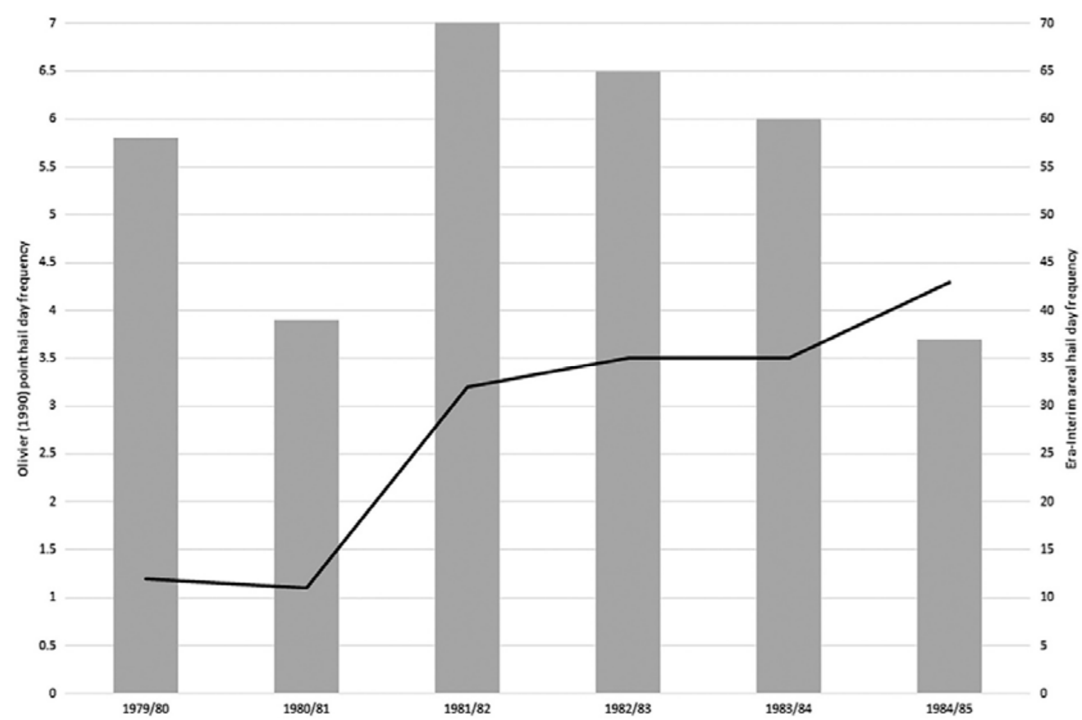

Figure 5. The annual point value HDF over South-Eastern Gauteng and parts of north west province according to Olivier (1990) (indicated by the line) and the areal EIH HDF for hail greater than 1 cm in diameter (indicated by the bar graph) between 1979/80 and 1984/85

The datasets cannot be expected to be in perfect agreement as there are differences in the way hail days are determined and in the meaning of HDF between the two datasets. Olivier (1990) defined a hail day in a homogeneous area when any of the stations in the area reported hail. An EIH a hail day is defined as a day when the average ensemble hail size is larger than 1 cm at an ERA-Interim grid point and the EIH HDF is valid for a grid box which is about 6 250 km^2 in size. Nevertheless, there are similarities between the two graphs in Figure 5. The troughs and peaks align, except in 1984/85 when the data of Olivier (1990) show an increase in the hail day frequency from the previous year, whereas the EIH shows a decrease. Further analysis of the results of Olivier (1990) shows that there was also a sharp decrease in the hail day frequency in 1984/85 in the adjacent areas, similar to the EIH trend. One can deduce from Figure 5 that, for this short period, the EIH can capture similar trends as found in an observed hail climatology. It is therefore capable of distinguishing between favourable and unfavourable hail years.

The third important hail climatology over South Africa is that of Held (1973 and 1974) and Carte and Held (1978). They established a hail observation network over an area of 2 800 km^2 in the Witwatersrand, which included both Johannesburg and Pretoria (see Figure 3). This area coincides to a large degree with the current Gauteng. The methodology they employed was similar to that used in the Alberta Hail Project (Brimelow et al., 2002). The Witwatersrand study had between 700 and 1 000 hail observers initially, but after 1970, the observers increased to as many as 4 000. Carte and Held (1978) defined a hail day when there was at least one hail observation over the area and observations were done from 1962/63 to 1975/76. There were years, such as 1964/65, in which 95 hail days occurred and others, such as 1964/65 and 1971/72, with as few as 39 hail days. Table 1 shows the average number of hail days per annum (October 1962 to September 1972) in the Witwatersrand area for three hail sizes (Carte and Held, 1978). The EIH hail day frequency in Table 1 was determined by calculating the average annual frequency of days with hail larger than 0.5 cm, 1 cm and 3 cm for the entire period from 1979 to 2017 across three ERA-Interim grid points over Gauteng. The three grid points are the two southern points in Figure 3 as well as the grid point in the north-east. The area represented by the three ERA grid boxes is approximately 18 750 km^2 in size and about 6.5 times the size of Carte and Held's area. All three grid points were chosen for comparison as the Carte and Held area partly lies in the geographical area covered by the three grid boxes. Similar to Carte and Held (1978), in EIH a day was considered a hail day when the hail prediction in at least one grid point exceeded the threshold. The average EIH HDF over Gauteng is consistently fewer than Carte and Held's hail days (Table 1), except for days with hail larger than 3 cm, during which the EIH climatology had more than double the number of hail days per annum than determined by Carte and Held (1978).

TABLE 1. The Carte and Held (1978) HDF per annum over the Witwatersrand and the EIH HDF for all hail (diameter of more than 0.5 cm, more than 1 cm and more than 3 cm)

	All hail days	Hail bigger than 1 cm	Hail bigger than 3 cm
Carte and Held	67	41	3
EIH in Gauteng	64	36	7

Note: The Carte and Held (1978) frequencies were determined from October 1962 to September 1972 over an area of 2,800 km^2, while the EIH frequencies are between 1979 and 2017 and for an area of 18,750 km^2 or three ERA-Interim grid boxes

The results of the comparison of the EIH climatology with MMI Holdings data and with the climatology of Carte and Held (1978) are similar in that there is an indication of an over-estimation of the frequency of large hail events (diameters larger than 3 cm), and a slight under-estimation of small hail events (diameters of 1 cm). Individual storms are not resolved by ERA-Interim and disparity may exist on individual days. However, the EIH climatology can resolve the larger-scale circulation adequately and provides detail about hail frequencies that are not available from the observed climatologies.

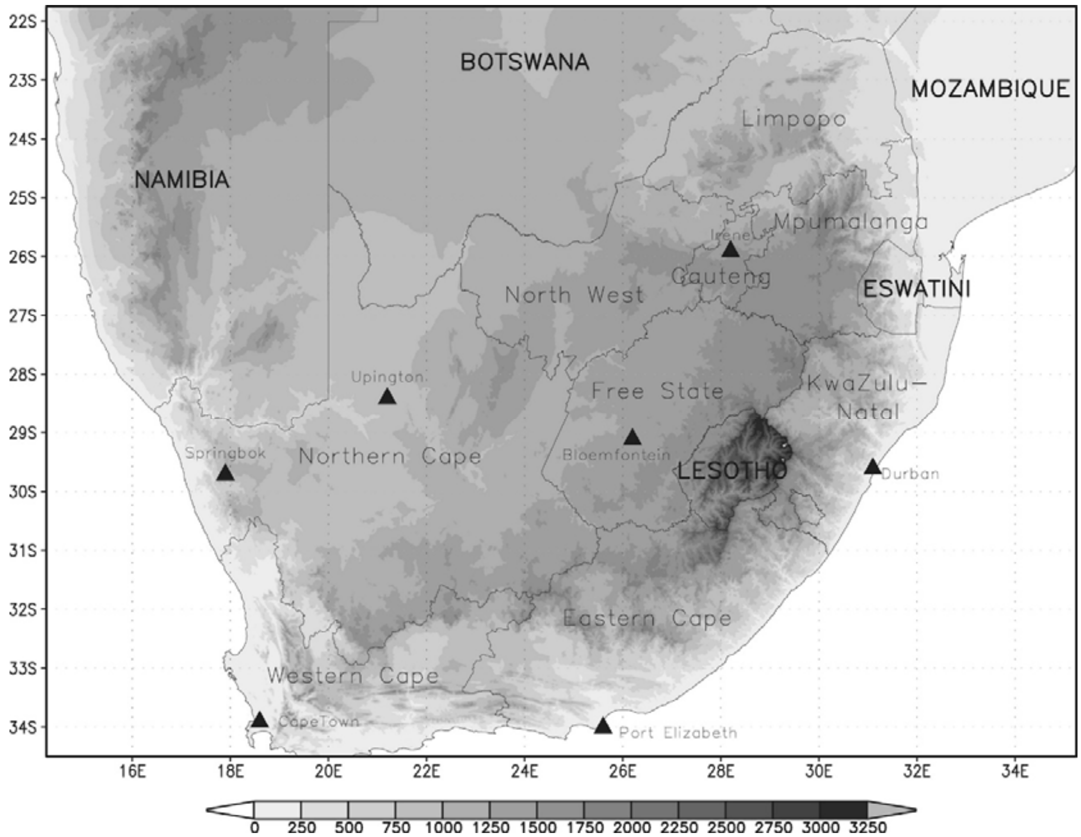

Figure 6. The ERA-Interim annual HDF between 1979 and 2017 for hail with a diameter greater than 1 cm (a) and greater than 3 cm (b). The dotted lines in (a) are the percentage of hail events that occur in austral summer (October–March). The triangles indicate the four locations where monthly HDF are investigated in Figure 8

5. Results

The EIH climatology (see Figure 6a) is compared to the observed climatology of Le Roux and Olivier (1996) as depicted in Figure 4. Figure 6a shows the areal EIH HDF1 for hail with diameters of more than 1 cm, while the HDF in Figure 4 represents point observation of hail with diameters greater than 0.5 cm. The EIH hail day frequencies in Figure 6 and 9 were determined by calculating the average annual frequency of days with hail larger than 1 cm and 3 cm for every ERA-Interim grid box. The HDF data in Figure 4 are point values, while the HDF data in Figure 6a are areal values in the 0.75° ERA-Interim grid box (area of approximately 6 250 km^2). Carte and Held (1978) compared the areal hail frequency to the point hail frequency and found an increase in the number of hail days with an increasing area. Over the Witwatersrand, the authors found that the hail frequency for an area over 1 000 km^2 is about a factor of 9 higher than the point frequency. The observed HDF of 3 to 5 at a station in Gauteng in Figure 4, therefore, compares well with the HDF1 count of 20 - 30 in Figure 6a.

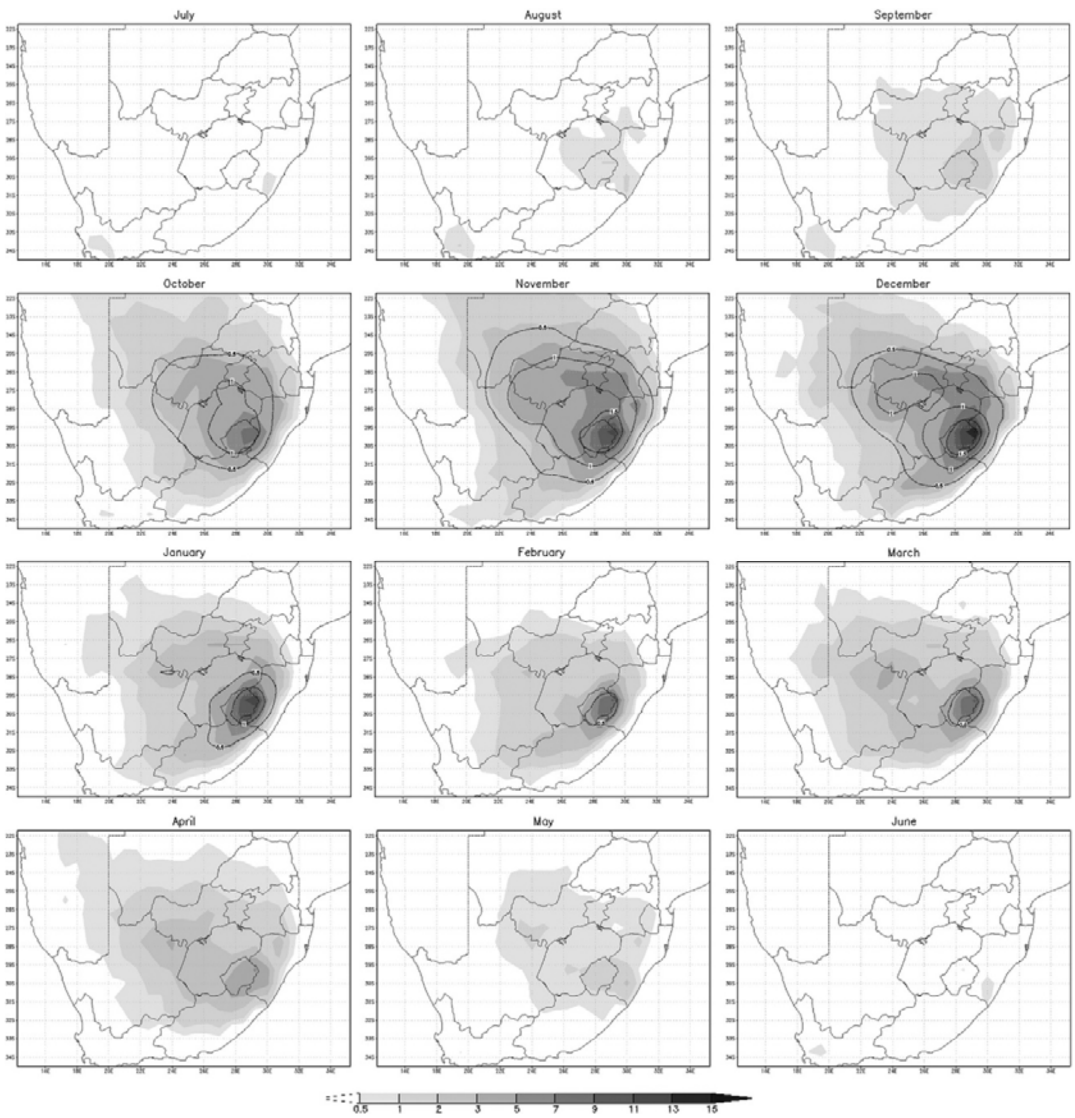

Figure 7. The ERA-Interim monthly HDF for hail with diameters greater than 1 cm for four locations in South Africa. The locations are indicated in Figure 6

There is very good agreement between figures 6 and 8a. For instance, note the area of higher frequency (HDF 5-7 in Figure 4 and 15-20 in Figure 6a) over the tri-province border of the Northern Cape, Eastern Cape and Free State provinces. The western boundary of hail activity over the Northern Cape (Figure 4) is aligned with the HDF > 5 in Figure 6a. The highest HDF on both images is over the eastern parts of Lesotho with tight gradients between the coast of KwaZulu-Natal and the mountains. The mountain peaks in Lesotho rise to over 3 000 m above mean sea level, and the same relationship between hail occurrence and altitude is also evident in the EIH data. Relatively high frequencies over the Witwatersrand that extend to the escarpment of Mpumalanga are also observed.

One of the noticeable differences between these two maps is that HDF1 over Mpumalanga in the EIH climatology (Figure 6a) is not the same as the frequency over Lesotho, as is the case in Figure 4. It is conceivable that hail would have been under-reported over the Kingdom of Lesotho for the period of validity in Figure 4. Lesotho is a rural area with significant mountain ranges over most of the country and only a few manned synoptic weather stations. Furthermore, the EIH climatology extends an area of higher HDF1 into the south-western parts of the North West province, which is absent in the climatology of Le Roux and Olivier (1996). The area of higher HDF1 in the EIH climatology (Figure 6a) occurs in the elevated terrain over the North West province into the Northern Cape (Figure 1). There was a small number of manned weather stations in this area and this may help to explain the absence of a higher hail day frequency in this area in Figure 4. Prein and Holland (2018) identified the same area as having a higher probability of hail per year and Blamey et al. (2017) extended their area of higher frequency of severe environmental days to this part of the North West province from October to December.

The EIH climatology provides information that was not previously available over the winter rainfall areas and outside the borders of South Africa. The mountains of the southern and western Cape are predicted to receive five to ten hail days per annum, and between 10 and 20 hail days are expected over southern Botswana. This area is the corridor through which moist tropical air flows from the Intertropical Convergence Zone (ITCZ) into South Africa in summer, and in which it encounters cold mid-tropospheric westerly waves (Taljaard, 1995), making conditions ideal for hailstorm formation. There is also a high frequency of cloud bands, or tropical temperate troughs, in this area (Hart et al., 2013).

In the EIH climatology, most hail days are predicted to occur in summer (October to March) with more than 80% of hail days anticipated in summer over most of southern Africa (see the dotted lines in Figure 6a). In contrast, over the extreme south-western parts of the country, 70% of hail days are predicted to occur during the winter months even though the number of hail days is only between 1-5 per annum. The low frequency of hail in the EIH climatology in the winter rainfall region is consistent with that of Schulze (1965) and explains why Le Roux and Olivier (1996) did not consider winter rainfall areas in their research.

The EIH climatology also provides information on the frequency of large hail that was not previously available. The HDF3 (see Figure 6b) is predicted to be as high as 13 over eastern Lesotho with generally high values over the Drakensberg. Southern Gauteng and south-western North West province have an expected occurrence of more than five days per annum with HDF3 (also see Table 1). HDF3 is projected to be less than one day per annum over the western half of the country in the EIH climatology. For the entire area predicted to have HDF3 of more than one day, the percentage occurrence in summer is more than 90% and approaching 100% over Lesotho (not shown). These results should be viewed in the light of the

EIH's overestimation of the frequency of hail larger than 3 cm. Although small hailstones are predicted to occur over the Western Cape in winter from extra-tropical weather systems (i.e. mid-latitude cyclones, cold fronts or cut-off lows), the HAILCAST climatology reveals that large hailstones are rare and seldom occur, even in winter.

In the EIH hail climatology, most hail is predicted to occur at 1200 UTC (1400 South African local time) when surface temperatures reach close to maximum (not shown). Warmer surface temperatures cause higher CAPE values (Lepore et al., 2015) and an increase in the temperature lapse rate in the lower troposphere, enhancing instability. Throughout southern Africa, more than 80% of hail events are predicted to occur at 1200 UTC and as high as 95% over the high ground in KwaZulu-Natal and the Highveld of Mpumalanga and Gauteng.

The monthly HDF is shown in Figure 7. During June and July, the area receiving hail is predicted to be limited to the mountains of the Western Cape and southern KwaZulu-Natal with HDF1 of 0.5 - 1. During August and September, the geographic area with hail is predicted to expand over the summer rainfall area, while the low number of hail days in the south-west lingers. In October, which marks the beginning of the hail season in the interior of southern Africa (Olivier, 1990), the HDF1 is predicted to be 3 to 5 over the eastern interior. In Lesotho, the HDF is more than 5.

For hail with diameters greater than 3 cm, the HDF3 more than 1 (dotted lines) is confined to the eastern escarpment and the Witwatersrand in October. During October and November, the mid and upper troposphere is relatively cold after winter, while surface temperatures rise quickly, increasing lower tropospheric temperature lapse rates. In spring ridging Atlantic Ocean Highs (AOH) advect moisture over the Mozambique Channel into South-Africa (Ndarana et al.,

2018) and the availability of surface moisture and steep vertical temperature lapse rates make conditions during early summer ideal for hail (Simpson and Dyson, 2018).

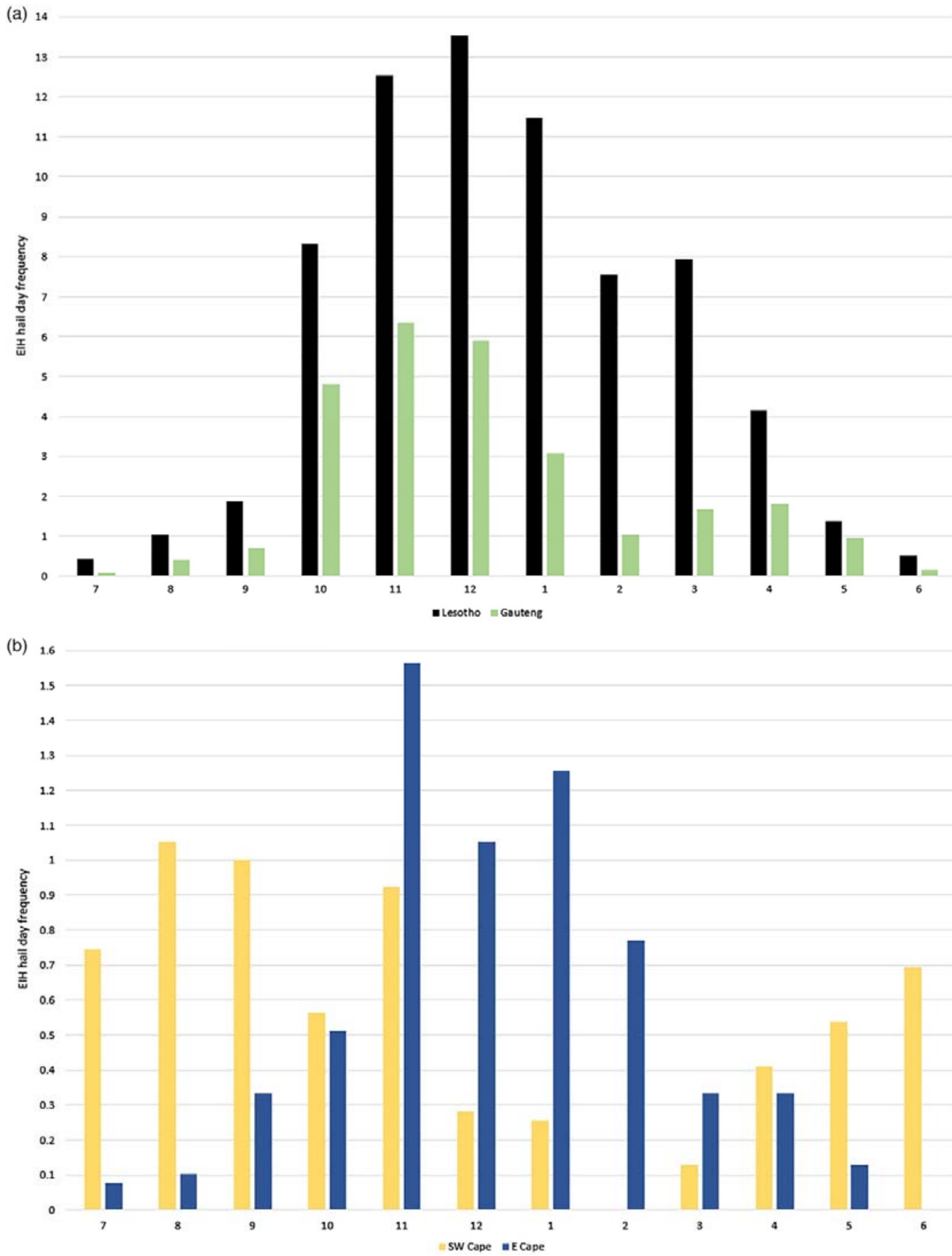

Figure 8. The ERA-Interim monthly HDF for hail with diameters greater than 1 cm for four locationsin South Africa. The locations are indicated in Figure 6.

The geographic area that receives hail is modelled to expand during November and included the eastern half of Namibia and the mountains of the Eastern Cape. Over the mountains of the Western Cape, a small number of hail days continues to be predicted, only disappearing in December. During November, a large portion of the eastern interior is expected to have HDF1 of more than 5 and Lesotho has an HDF1 of more than 10. The area in which larger hail, with an HDF3 of more than 1, is predicted to extend westwards to include the North West province and the Free State, as well as south-eastern Botswana.

During December, the extreme north-eastern extremes of South Africa is predicted to become largely hail free (with an HDF1 of less than 0.5) with a westward shift of HDF1 of more than 1 into Namibia and Botswana. Over South Africa, the expected occurrence of HDF3 generally decreases after November, the exception being the Lesotho Highlands, where it continues to increase into December. During January and February, the values of HDF1 and HDF3 decrease throughout southern Africa. During this time, the circulation over South Africa becomes distinctly tropical (Dyson et al., 2015) and formation of hailstorms is expected to decrease with relatively warm mid and upper tropospheric temperatures. For most locations over the summer rainfall area, the HDF decreases from March to June as winter begins.

The monthly distribution of HDF1 is further analysed at a few locations across South Africa (Figure 8). These locations are Gauteng (GP) and Lesotho (LE), which represent the summer rainfall area, the Eastern Cape (EC), represents the all-year rainfall area, and the Western Cape (WC), has winter rainfall (see the locations indicated on Figure 6). In Gauteng, the HDF1 is predicted to be at its highest during November and decreases towards February with a slight increase in March and April (Figure 8a). Lesotho is modelled to have almost double the number of hail days as Gauteng, and here December is the month predicted to have the most hail days.

The late summer or early autumn variation in HDF1 that is visible over Gauteng is also seen over Lesotho. During March and April, the circulation returns to extra-tropical with a decrease in the mid and upper tropospheric temperatures; however, surface moisture is still available for convection (Dyson et al., 2015) explaining the increase in hail days during these 2 months.

The Western and Eastern Cape are predicted to have considerably fewer hail days than the summer rainfall area (see Figure 8b). The highest monthly HDF1 is during November over the Eastern Cape with a value of just over 1.5. In the Western Cape, values are generally predicted to be less than 1. As is the case with most of the summer rainfall areas, the highest monthly HDF is expected in November over the Eastern Cape. The number of hail days is forecast to decreases during December but increases again in January. In the winter rainfall area, the months with the highest HDF1 are expected to be August and September. HDF1 is modelled to decrease during October but increases again in November. February is predicted to have no hail days in the Western Cape.

6. Discussion and recommendations

A state-of-the-art hail model, HAILCAST (Brimelow et al., 2002), is used to predict hail size for 38 years over southern Africa. HAILCAST is run using pseudo-soundings created from ERA-Interim data (Dee et al., 2011), and surface temperature and dewpoint temperatures are perturbed for each sounding to create an ensemble of forecasts. The mean of the ensemble of forecasts is used to calculate hail day frequencies for different size categories.

The EIH forecast was compared to insurance hail claims for the hail event of November 2013 over Gauteng. The results are encouraging, and there is a good agreement between the EIH forecast and geographic distribution of the hail insurance claims over Gauteng. EIH forecasts appear to find it difficult to identify the exact location of the hail in an area with complex topography such as Gauteng. Furthermore, the EIH forecast over-forecast the number of hail events and hail size when compared to insurance hail claims.

The hail climatology determined from the ERA-Interim data is compared to previous notable hail climatologies over southern Africa. The EIH climatology compared well to that of Carte and Held (1978) over Gauteng. The frequency of hail days in both climatologies is comparable for different hail sizes. There is, however, an over-estimation in the EIH climatology for hail larger than 3 cm in diameter. The EIH hail day frequency compares well to the climatology of Le Roux and Olivier (1996). Detail that was previously unavailable, such as the seasonal and temporal distribution of hail, is now available from the EIH climatology. For the first time in South Africa, there is a climatology for hail with diameters greater than 3 cm. Information is also now available for the winter rainfall areas and for countries bordering South Africa.

The EIH results indicate that Lesotho is the geographic area with the most hail days, with an areal average of between 50 and 70 hail days per annum. Lesotho is also the highest area of the South African region. There is a good association between topography and hail day frequency, with the Highveld of eastern South Africa receiving more hail days (20 to 30) than the surrounding areas. Hail is rare in the Western Cape, but the mountains receive between five and 10 days of hail per annum.

November is the peak of the hail season for most of the summer rainfall area, except for Lesotho, where the highest number of hail days occurs during December. In the summer rainfall area, the hail day frequency decreases from November to February with a slight upsurge in March and April. These results compare well to the findings of Carte and Held

(1978) over the Highveld of South-Africa. In the Western Cape, August is the month with the highest number of hail days, but November is a significant hail month, even in this winter rainfall area. In the Eastern Cape, November and January are prominent hail months. During summer, there is a general westward shift in the geographic area in respect of hail per month, similar to the westward movement of the monthly accumulated 50 mm isohyet in summer as described by Taljaard (1996). This westward shift in severe environments is not reflected in Blamey et al. (2017). In their study, the occurrence of severe environmental days reaches farthest west over the Highveld in October-November, while in February-March severe environmental days are confined primarily to the southeast coast and adjacent interior.

Results in this paper show that the Highveld of South Africa has a high frequency of hail days. This is similar to results from Schulze (1965) and Blamey et al. (2017) where the Highveld is favoured for severe environment days. In contrast to the results of Schulze (1965), Le Roux and Olivier (1996), as well as the results in this paper, Blamey et al. (2017), did not identify severe environment days over eastern Lesotho. The satellite-derived climatology of hail of Ni et al. (2017) also identified the higher frequency of hail over the mountains of Lesotho while Brooks et al. (2003) and Blamey et al. (2017) identified the area with the most severe environment days along the south-east coast of South Africa. This area does not feature prominently in our results.

There is in general very good agreement between the results presented in this research and previous work, except for eastern Lesotho and KwaZulu-Natal. The difference in the results from ERA-Interim and those from Blamey et al. (2017) over this area could be attributed to the difference in reanalysis datasets. The Climate Forecast Systems Reanalysis utilized by Blamey has a resolution of 0.5°, while ERA-Interim reanalysis has a horizontal resolution of 0.75°.

Results from Gijben (2012) indicate a relatively low cloud to ground lightning frequency over eastern Lesotho, while satellite-derived climatologies (e.g. Ni et al. (2017)) have a high frequency of severe weather conditions over this area. The discrepancies in results from different researchers over KwaZulu-Natal and Lesotho warrants further investigation into severe weather environments.

The value of HAILCAST is illustrated by comparing our results with climatologies based on atmospheric parameters alone. HAILCAST models the growth of hail from first principles and provides a hail size diameter. Even though the ingredients for severe storms may be present, it does not necessarily result in convective development and hail.

Future work will include an alternative method to analyse the probabilistic hail hazard, by investigating the relationship between the frequency of events and event sizes. This methodology will aim to estimate the hail hazard per spatial grid box, including recurrence parameters while taking into consideration uncertainty in the hail size determination and uncertainty associated with the applied hail occurrence model. This can be used as prior information in the probabilistic assessment of the hail risk for among others the insurance industry.

Additionally, the methodology described in this paper should be repeated on Numerical Weather Prediction data with finer horizontal, vertical and temporal resolutions. Some of the issues encountered in areas of steep topography could be better resolved in data with finer horizontal resolution. It is also conceivable that an increase in the number of vertical levels could deal better with the steep vertical gradients that are required for hail formation. Having data available at more regular intervals will improve the temporal distribution of hail forecast.

It should also be tested whether a more refined EIH climatology is possible by using a mask to exclude non-convective events. These masks could include the convective precipitation forecast of ERA-Interim (Brimelow and Reuter, 2009), lightning data or cloud top temperatures from satellite.

The ERA-Interim hail climatology provides information that was previously unavailable and covers a large geographic domain. Results are reliable and consistent with previous climatologies over South Africa. However, the ERA-Interim pseudo-soundings and the output of the HAILCAST model remain proxies of reality. Hail observations should be monitored and continuously compared to these results. The climatological results should also be tested for robustness in other areas of the globe. The methodology described in this paper should be applied to appropriate climate model data to investigate hail occurrence in a future climate.

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