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Abstract | Hailstorms are dangerous and costly phenomena that are expected to change in response to a warming climate. In this Review, we summarize current knowledge of climate change effects on hailstorms. As a result of anthropogenic warming, it is generally anticipated that low-level moisture and convective instability will increase, raising hailstorm likelihood and enabling the formation of larger hailstones; the melting height will rise, enhancing hail melt and increasing the average size of surviving hailstones; and vertical wind shear will decrease overall, with limited influence on the overall hailstorm activity, owing to a predominance of other factors. Given geographic differences and offsetting interactions in these projected environmental changes, there is spatial heterogeneity in hailstorm responses. Observations and modelling lead to the general expectation that hailstorm frequency will increase in Australia and Europe, but decrease in East Asia and North America, while hail severity will increase in most regions. However, these projected changes show marked spatial and temporal variability. Owing to a dearth of long-term observations, as well as incomplete process understanding and limited convection-permitting modelling studies, current and future climate change effects on hailstorms remain highly uncertain. Future studies should focus on detailed processes and account for non-stationarities in proxy relationships.

Hail is ice precipitation larger than 5 mm in diameter formed in thunderstorms[1]. Hail particles, known as hailstones, form inside the region of the storm where temperatures are below freezing and there is abundant supercooled liquid water in coexistence with ice particles. Ice particles are drawn through the storm by its internal winds and can grow quickly in size through collisions with supercooled droplets, which collect on and freeze to their surfaces[2]. A growing hailstone is kept aloft by strong updraughts in the storm, until it exits the updraught or becomes too heavy to be supported, and falls. Typically, hailstones enter warmer air and partially or completely melt as they fall[3]. When they reach the surface, hailstones exceeding 2 cm in diameter are considered severe[4] and can be destructive[5].

Convective storms that produce hailstones (hereafter, 'hailstorms') endanger lives and property and cause considerable damage across the world[6], affecting buildings and vehicles[7], agriculture[8] and ecosystems[9]. Hailstorms inflict serious financial losses, totalling roughly US$10 billion per year in the USA alone[10], and a single severe-hail event can cause more than US$1 billion in damage[11,12]. The largest losses are sustained when hail falls over the highly concentrated assets associated with densely populated areas[5]. Examples include the record-breaking 1999 hailstorm over Sydney, Australia, which featured hailstones larger than 11 cm in diameter and caused AUD$1.74 billion in insured losses[13]; the 2012 hailstorm in Phoenix, Arizona, USA, which produced hailstones of up to 10 cm in diameter and caused US$4 billion in damage[12]; and the 2013 series of hailstorms over central and southwest Germany that caused an estimated total economic loss of €3.6 billion[5].

Anthropogenic climate change is expected to modify the environments in which hailstorms typically develop. In particular, three properties are likely to change, albeit with marked geographic variability: low-level moisture and, thus, convective instability[4,14–19]; melting level height (MLH)[20–23]; and vertical wind shear[14,16,17,22]. These environmental characteristics can, in turn, affect hailstorm frequency[24–28] and severity[21,28–31], and, thus, damage and losses, motivating assessment of contemporary and future hail changes. However, owing to limited direct observations of hail, incomplete understanding of the microphysical and dynamical processes, and the difficulties inherent in running models at sufficient resolution to provide reliable hail information, it remains highly uncertain how hailstorms will respond to warming[4,32–36].

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Key points

- Efforts to understand the effects of climate change on hail are complicated by the small scale and relative rarity of hailstorms, which make hail hard to observe and model.
- Climate change affects low-level moisture and convective instability, microphysical processes and vertical wind shear, all of which are relevant to hail formation and properties.
- A scarcity of hail observations and high-resolution modelling studies, and gaps in the understanding of physical processes, contribute to the current high uncertainty around the effects of climate change on hailstorms worldwide.
- General indications based on observations and modelling are of overall hailstorm frequency increasing in Australia, slightly increasing in Europe and decreasing in East Asia and the USA.
- In most regions, hailstorm severity is expected to increase with climate change.
- Long-term observations and high-resolution modelling are crucial to understanding the effects of climate change on hailstorms. Future studies should focus on furthering process understanding and improving proxy relationships.

In this Review, we summarize current knowledge on the effects of climate change on hailstorms, with a focus on the atmospheric variables most relevant to hail. We first give an overview of how hail forms and the main processes involved, before discussing the impacts of climate change on three factors: moisture and convective instability, microphysical processes and vertical wind shear. For each factor, we explain how its possible changes in response to the warming climate relate to hailstorms. We then provide details of previous results organized by geographical region, concentrating on studies that are hail-specific, rather than on more general studies of changes in convective activity, and conclude with recommendations for future study.

Hail formation

Hail forms within convective storms (FIG. 1) that have regions containing supercooled liquid water and ice and sufficiently strong updraughts (typically, at least 15 m s^{-1}) to support growing hailstones[2]. The specific conditions required for hail lead to a heterogeneous spatial distribution of global hail probability (FIG. 2). The processes by which hailstones initiate, grow and melt are called microphysical processes[2,37]. We briefly discuss convection and hail formation in this section; further details can be found elsewhere[2,6,37–39].

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Convection occurs when air parcels are sufficiently lifted by a triggering mechanism near the ground in a convectively unstable atmosphere. Triggering mechanisms include local heating or convergent winds, fronts and orographically driven circulations[40,41]. The atmosphere is convectively unstable when the vertical temperature and moisture profiles are such that an air parcel lifted above a certain height — its level of free convection — is more buoyant than its surroundings over a sufficient vertical depth of the troposphere. A parcel lifted above its level of free convection will continue to rise owing to its buoyancy, forming an updraught that draws moist air upwards. Convective inhibition (CIN) is a measure of the amount of energy that must be supplied in order for air parcels to reach their level of free convection. Mechanisms for the generation of CIN in lower-atmospheric levels include daytime heating of elevated terrain and differential advection resulting in vertical air-mass stratification[42], and air-mass subsidence with associated dry adiabatic warming[43]. Moderate CIN is generally favourable for intense deep convection, as it allows for the build-up of stronger convective instability and explosive convective development[19]. If the triggering mechanism is strong enough for the air parcel to overcome the CIN, the parcel will rise and convection will occur.

During the parcel's ascent, the water it contains cools and condenses into cloud droplets, releasing latent heat and slowing the parcel's rate of cooling, which further increases its buoyancy. The temperature of the atmosphere decreases with height, and the altitude at which the wet-bulb temperature is 0 °C is the MLH[23,44] (FIG. 1a). Above the MLH, condensed water in the air parcel can freeze into ice around nuclei called ice-nucleating particles (INPs)[37,45]. However, while the temperature remains above approximately −40 °C, much of the condensed water in the air parcel will remain in the liquid state and becomes 'supercooled'[2].

Hailstones grow when hail embryos, which are typically frozen raindrops or small ice pellets called graupel[46], collide with supercooled liquid, which freezes onto their surfaces[2]. Growth occurs on a continuum between 'dry growth', during which all collected water freezes onto the hailstone's surface, resulting in a low-density layer of air and ice within the hailstone, and 'wet growth', during which some of the water remains liquid long enough to fill any air gaps in the ice before freezing, resulting in ice with a higher density and fewer air bubbles[37]. Dissected hailstones often show multiple layers of different growth types[46]. The overall size and density of a hailstone is positively correlated with its terminal fall speed[2].

Larger hailstones are more damaging than smaller ones: assuming spherical hailstones, a hailstone's kinetic energy scales approximately with the fourth power of its diameter[47,48]. Predicting the maximum size a hailstone can attain is, thus, of particular interest. For an embryo to grow into a large hailstone, there must be enough available supercooled liquid water for it to collect. Moreover, the concentration of hail embryos can also limit hailstone size, as more embryos competing for the available supercooled water results in smaller hailstones[2]. A large hailstone also requires sufficient

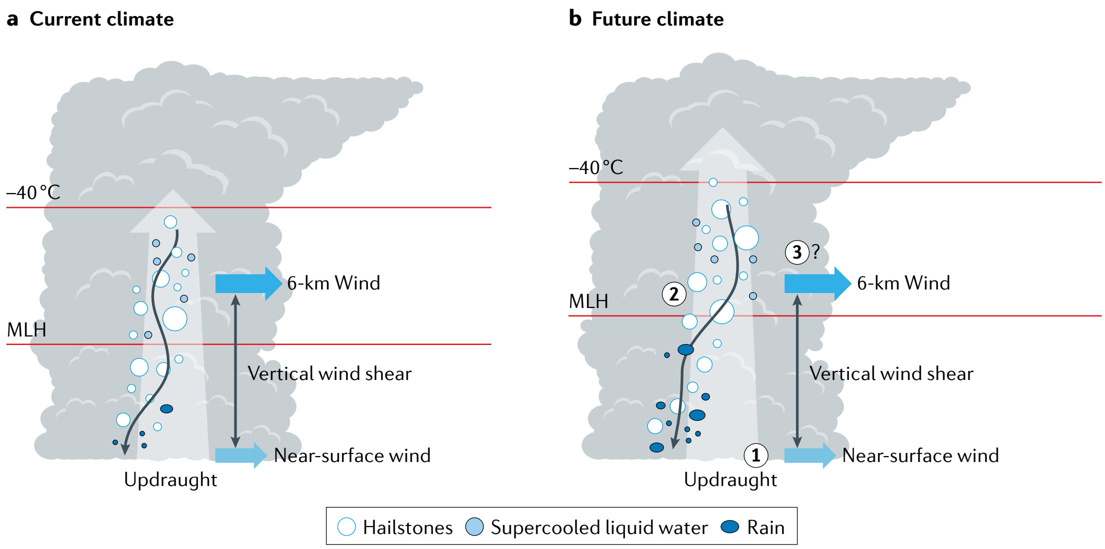

Fig. 1 | **Hail-relevant atmospheric phenomena in current and future climates.** The expected changes in hail-relevant atmospheric phenomena between the current (panel **a**) and future (panel **b**) climates. The numbers in panel **b** correspond to the following changes: (1) increased low-level moisture leads to increased convective instability and updraught strength; (2) an increase in the melting level height (MLH) leads to enhanced melting of hailstones and a shift in the distribution of hailstone sizes towards larger hailstones; and (3) changes in vertical wind shear may affect storm structure and hailstone trajectories, but are generally overshadowed by instability changes.

time to grow, with the growth time controlled by the updraught strength and the embryo's trajectory through the storm. To become large, the embryo must follow a trajectory that maximizes time spent in the relatively narrow growth region of the updraught in which there is abundant supercooled liquid water[31,49].

A hailstone can only be supported within the storm while its fall speed is less than or equal to the speed of the updraught suspending it; thus, the updraught speed limits the maximum hailstone size, and the maximum vertical velocity correlates with the maximum size of hailstones that can be produced[31,50,51]. As too strong an updraught may eject the embryo out of the high-growth region[2] and most hailstone growth occurs on relatively simple growth trajectories[2], such as a single pass across the updraught[52], the production of large hailstones is associated with a broad and moderate-strength storm updraught[31,50,52] in which hail embryos can be suspended as they grow. By contrast, abundant supercooled liquid and large numbers of embryos without sufficient updraught strength or growth time may result in large accumulations of small hail[53].

Hail embryo and hailstone trajectories, and, therefore, maximum hailstone size, are influenced by the lower-tropospheric vertical wind shear[31] — that is, the difference in wind velocity with height (FIG. 1a). Wind shear also organizes the thunderstorm and is key to its severity[30,31,38], with damaging hail most likely to occur in supercell-type thunderstorms[16,50,54] or organized multicellular convection[55], both of which require moderate to high shear to form[16,38,50,54]. Studies of hail-favouring environments have typically used vertical wind shear as a proxy variable[14,56–58], and weighted combinations of convective instability and shear indices are often used as a discriminating variable for severe-thunderstorm occurrence[57,59,60]. In both Australia and North America, wind shear is at least as important an atmospheric 'ingredient' as convective instability for the development of severe thunderstorms[16,60].

The last important factor affecting maximum hailstone size is the amount of melting of the hailstones as they fall below the MLH towards the ground. It is easier for small hailstones to melt completely than larger hailstones that fall more quickly and have more mass[37], and, thus, melting during falling shifts the hailstone size distribution towards larger hailstones[61]. Note that the exact hailstone diameter that constitutes 'large' or 'very large' hail is a matter of definition and varies in the literature. In this Review, we refer to severe hail as that with hailstones of at least 2 cm in diameter, large hail as that with at least 3.5-cm diameter hailstones and very large hail as that with hailstones of at least 5 cm in diameter.

Process-level climate change effects

The limitations of hail observations and simulations make it essential that analyses of climate change effects on hailstorms are based on process-level understanding. That is, the effects of climate change on hail-related atmospheric variables and related hail-growth and melting processes, as well as the complex interactions between their changes, must be studied to determine the combined effects on hail. In this section, we discuss the effects of climate change on convective instability, vertical wind shear and microphysical processes, and their relationships to observed and simulated effects of climate change on hailstorms (FIG. 1b).

Moisture and convective instability

Owing to anthropogenic warming, tropospheric water vapour in the future atmosphere is expected to increase by ~7% per °C of warming, consistent with the Clausius–Clapeyron relation[34,62]. More low-level moisture

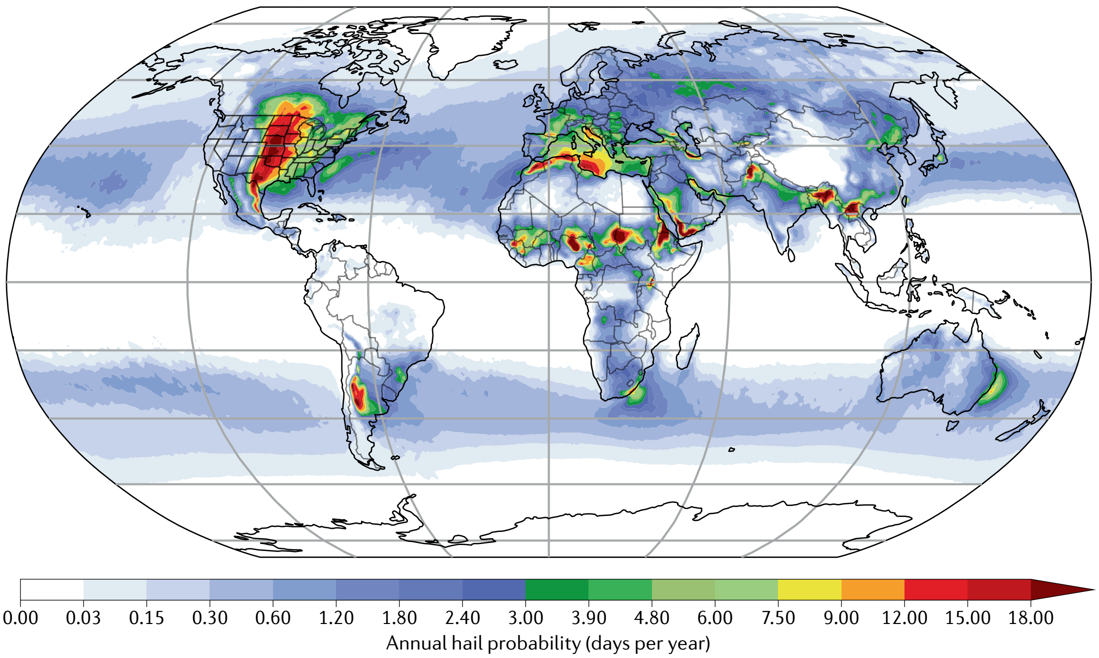

Fig. 2 | **Global hail probability.** The global estimated average annual probability of hail with a diameter >2.5 cm, normalized to areas of 100 km × 100 km, for 1979–2015. Hail is generally a rare event at any given location. Adapted from REF.[85], CC BY 4.0.

combined with higher temperatures means that a larger amount of potential energy can be released through the condensation of water vapour in a rising air parcel, thus increasing convective instability[4,17–19]. Future projections show expected increases in convective instability over Europe[63], the USA[14,15,17,19,57,64], Australia[65] and China[20]. Although the projected trend is generally upward[4,16,35,66], agreement between models is not universal, and changes can be regionally dependant. For example, changes to convective instability are projected to have seasonal dependence, with decreases in the warm season and increases in the cool season in Europe[67].

Thunderstorm initiation and intensity are very sensitive to low-level moisture and temperature, and the difference between environments with no thunderstorm initiation and those with intense convection can be as small as 1 °C in temperature or 1 g kg^{-1} in moisture content[68]. Hailstone size is also highly sensitive to these factors[69–71]. Greater initial moisture content in thunderstorms is associated with increased hail precipitation rates[72], and observed and projected increases in hail frequency are linked to increased convective instability[24–28]. A rise in convective instability is expected to lead to the production of larger hail[28], owing to stronger updraughts[15,22].

It is not guaranteed, however, that greater convective instability will always lead to more frequent severe thunderstorms or hailstorms. Buoyancy is necessary but not sufficient for convection[28,73], and the effects of increasing convective instability on hail can be offset by a coincident change in other hail-relevant variables. For example, a warming of the mid-troposphere can stabilize the lower atmosphere, leading to higher CIN[4]. An increase in overall convective instability can, therefore, be offset by coincident augmentation of the CIN, which can reduce the occurrence of convection and hail[17,19,22,74,75]. The accompanying rise in MLH driven by this lower-tropospheric to mid-tropospheric warming may also offset the effect of greater convective instability by causing hail that forms aloft to melt before it reaches the ground[20,21,51]. Furthermore, greater atmospheric moisture capacity may dampen the updraught strength by making it possible for more condensate to form, even as parcel-based convective instability measures increase[73].

Vertical wind shear

Overall deep-tropospheric vertical wind shear is expected to reduce with climate change[14,16,17], but such changes are difficult to quantify[16]. Expected variations in jet streams[33,34,65] and storm tracks[33,34] that affect large-scale circulation may also have a role in vertical-wind-shear changes. Despite the importance of wind shear in the development of severe storms, including hailstorms[16,60], historical analyses and future projections generally show hailstorm changes that are driven less by changes in wind shear than by changes in convective instability[26,27,74,76,77] or MLH[20]. This outcome is because changes to wind shear either occur at times when hail is unlikely to form or are outweighed by the relatively greater effect of changes to instability or MLH. Thus, decreases in wind shear generally do not inhibit expected increases in the occurrence of thunderstorm environments driven by rising convective instability[14–16]. In the USA, projected decreases in wind shear are concentrated at times when convective instability is low[17]; in Australia, the expected decreases are too small to offset increases in convective instability[65]; and, in Europe, wind shear may instead increase when convective instability is high[63]. In addition, although variations in upper-level vertical wind shear modulate simulated supercell precipitation, the effect on surface hail is unknown[78].

Microphysical processes

Few studies consider climate change effects on hail microphysical processes, partly owing to the computational constraints of modelling hail processes completely, which mean that the microphysics is parameterized in numerical models[79]. The atmospheric INP concentration is related to the temperature and aerosol concentrations, but high uncertainty in the simplified relationships used to model ice nucleation has hampered attempts to link predictions of future aerosol concentrations to predicted future INP concentrations and their effects on microphysical processes[80].

In the warmer troposphere[33], convective cloud base temperatures and liquid water content may both increase in the future[81]. For example, simulations over the USA show increases of cloud base temperature of up to 3.5 °C between 1970–1999 and 2070–2099 (REF.[81]), and projections show regional increases of 4–9.6% in maximum cloud liquid water content for March–September hail days between 1971–2000 and 2041–2070 over the USA[22]. Such increases could affect hail-growth types by allowing for more supercooled water above the MLH and encouraging the wet growth of larger, denser hail. The amount a hailstone melts below the MLH depends on the particle's size and density and the relative humidity and temperature profiles[3], as well as the length of time during which it melts while falling, which is determined by the MLH. Over land areas globally, the MLH has risen by 32 ± 14 m per decade during 1979–2010, reducing the risk of very large hail by 1.3 ± 0.2% per decade, with the greatest decreases in the tropics and subtropics[23]. Increased MLH has led to a shift towards fewer small and more large hailstones in observations in China[20,74,82] and France[29]. A similar shift in hail size in future projections for North America is also partially attributed to increased melting[21,22]. Changes in hailstone-size distribution affect melting and evaporation rates, downdraught strength and cold-pool intensity, which influence the amount of surface hail and even the storm structures produced[83]. Increased melting may reduce surface hailfall[22], even if hail production within storms increases[21]. However, because melting increases with increasing relative humidity[3], any reduction in relative humidity of the sub-cloud atmosphere may offset the effects of increased MLH to some degree[28].

To summarize, it is broadly expected that increased atmospheric temperature and low-level moisture will lead to increased instability, storm updraught strength and liquid water content, all of which support the formation of larger hail; a rising MLH will increase melting of smaller hail; and vertical-wind-shear changes are unlikely to strongly affect hailstorms. These changes underpin expectations that hail frequency at the ground should decrease with time, with larger hail becoming a more common occurrence.

Past and future changes by region

In this section, we outline observed and projected changes to hail by continent, considering past trends (FIG. 3) and future simulations (FIG. 4) for each region. There are considerable difficulties in estimating past hail trends: data time series are often too short for accurate trend analysis, sources such as hail reports or insurance-loss data often have inherent biases and point measurements are not spatially representative (BOX 1). Furthermore, not all studies report the statistical significance of derived trends. Unless otherwise stated, hail trends reported in this section are statistically significant (see the Supplementary Information for summaries of all studies).

Africa

There are areas of high hail hazard across Central and West Africa, as well as in South Africa, northern Morocco and Mediterranean regions of North Africa[84,85] (FIG. 2), but there are few studies on the effects of climate change on hail in Africa. Reanalysis data (1979–2016) show positive trends of up to approximately 0.3 cases of severe hail per year in northern Algeria and negative trends of up to 0.6 cases per year in northern Morocco[27]. Apart from these trends, past and projected changes to hailstorms in Africa remain unknown.

East Asia

Studies of hail trends in Asia have focused on China, where a large observational network has operated since the 1960s[86,87]. From 1960 to 1980, there was little change in hail frequency, but there was a steep decline from 1980 to 2012 that led to the hail frequency approximately halving[20,74,82,87,88]. There are some regional dependencies: the decrease in frequency is strongest in northern and northwestern China (since the early 1990s) and the Tibetan Plateau (since the early 1980s), and not statistically significant in the south[74]. The corresponding trends in annual hail days per decade (1960–2012) are −0.65 for the Tibetan Plateau, −0.32 for the north, −0.24 for the northwest and −0.07 for the south[74]. This decrease in hail frequency in China coincides with an increase in convective instability[20] offset by two factors: a weakening of the East Asian summer monsoon, which has reduced moisture transport[74,87], and a rising MLH[20], particularly on the Tibetan Plateau after 1980 (REFS[74,82]). An increase in CIN[74] and an increase in aerosol concentrations are also hypothesized to play a part in reducing hail frequency[20]. Mean vertical wind shear has decreased since the 1980s[82,87], but it is not thought to be the driving factor in determining hail frequency at the ground[20,74].

Trends in maximum hail size for elevations below 2,000 m in four Chinese regions are unclear[51]. Nationwide data show that, for severe hail, the hail-size distribution in China has shifted towards smaller sizes since 1980, with the annual mean diameter of severe hailstones decreasing by 1.7 mm per decade since the early 1990s[89]. The annual maximum hail size has decreased over 1980–2015, with regional trends in eastern China of approximately −0.7 mm per year[90]. Disaster records (1949–2012) show a recent increase in the area affected by hail damage in northwestern China[91], but statistical significance is not reported, and this result may be affected by coincident increases in population and, thus, reporting.

Decreasing hail-frequency trends are also observed elsewhere in East Asia. In Mongolia (1993–2013), a trend of −0.214 hail days per decade is attributed to decreasing

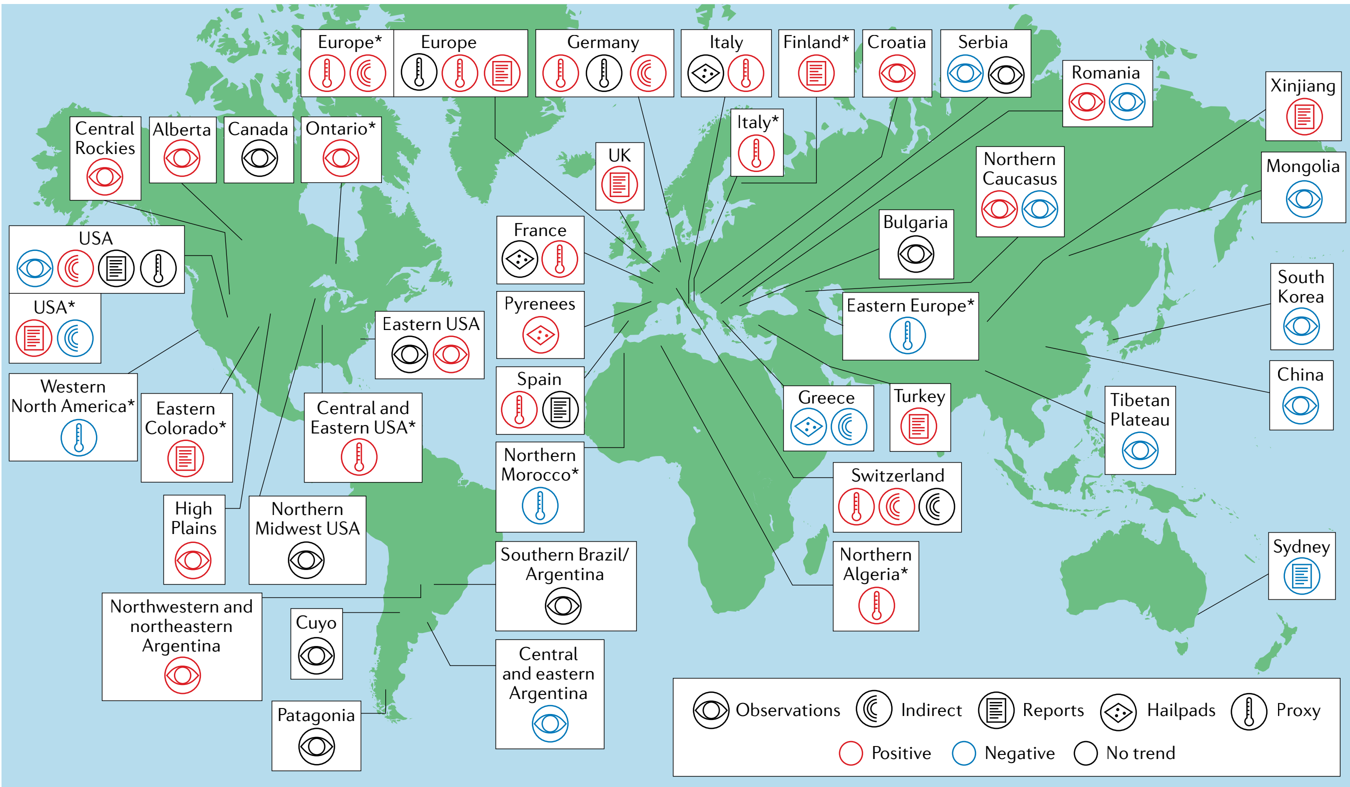

Fig. 3 | **Overview of past-trend studies and their conclusions on hail-frequency trends.** Observed hail-frequency trends show marked spatial variability. Geographic positions are approximate, and an increase in duration or hail-prone environments is interpreted here to indicate an increase in frequency. Indirect observations include radar, insurance data and tree-ring data. Proxy trends include regional climate models, sounding data, reanalysis data and synoptic data. An asterisk indicates that the conclusions are for larger hail (that is, severe hail, or that with a diameter of ≥0.75 inches and above). See Table 1 in the Supplementary Information for further details of the studies and the references.

convective instability and low-level moisture combined with increasing MLH[92]. In South Korea (1972–2013), there is an overall trend of −0.09 annual hail days per decade, with the decrease attributed to increasing MLH and decreasing bulk (0–6 km) wind shear[93]. No future projections for hail in Asia have been reported.

Europe

Past trends. No comprehensive and consistent estimates of trends in hail frequency or hail days based on direct observations are available for Europe[94]. The number of hail days observed at coarsely spaced weather stations has generally increased in central and western Europe, such as for Romania (1961–2014)[95] and for high-impact events in Catalonia in Spain (1994–2009)[96]. By contrast, trends are decreasing or not statistically significant further to the south and east, such as in Bulgaria (1961–2006)[97] and Serbia (1949–2012)[98]. Analyses of insurance claims, taking into account variability in the portfolio, show increases in hail days for Switzerland (crop damage; linear trend of +0.46 per year for 1949–1993)[8] and southwest Germany (building damage; +0.42 per year for 1983–2004)[24], likely resulting from an increase in hail-favouring weather patterns[8,99] and thermal instability[25]. In Switzerland, long-term (1939–1996) tree-ring data recording hail damage show an increase in activity[100] (significance unstated), but no trends in hail-affected footprint length, storm duration or average area are found in 15 years of radar data (2002–2016)[101]. Across Europe, the number of hailstorm reports has increased, but trends have not been statistically analysed, and the increase is mainly due to increased reporting[102].

Most valuable for trend analyses in Europe are hailpad observations, because of their long-term operation, the large number of stations included and the possibility to separate hailstone-size classes. At varying times since the 1970s, regional hailpad networks have been installed in Croatia[103], southwestern and southern France[104,105], and northeastern Italy[48]. In France and Italy, the network data show little overall trend in hail frequency[29,48,105–108] but show positive trends for large hail or derived quantities, such as hail kinetic energy[29,48,105]. In several cases, trends differ substantially between the stations, and even the trend directions may change between neighbouring stations[107]. In northeastern Italy (1975–2009), changes in hail frequency were not statistically significant[48,106], but extreme hail indices have increased, with a trend, for example, of 1.69% per year in the total hail kinetic energy of 90th percentile events[48]. This increase is interpreted as a general increase in hail severity[48].

Regional trends in the number of hail days in southwestern France are not statistically significant[29,105,108,109], with the exception of positive trends in the Pyrenees (1989–2014)[109]. Combined data from the Atlantic and

Pyrenean regions (1989–2009) show increases in hail size, and some indications suggest an approximately 6-year periodicity in hail frequency[105]. A correlation between summer mean minimum temperature and hail damage in France extrapolates to a 40% increase in hail damage per degree temperature increase[105,110]. In summer, the minimum overnight temperature is presumed to be an estimate of the low-level wet-bulb potential temperature for the following afternoon, which is related to atmospheric instability and, therefore, storm potential[110]. However, the extrapolation assumes stationarity of the correlation with climate change. Similar correlations have been found for the Netherlands[111], Switzerland[8] and Germany[112], but not Spain[113].

Environmental proxies computed from sounding data or reanalyses in general show moderate trends towards a higher potential for convection across large parts of Europe. Sounding data (1978–2009) reveal that the atmosphere has become more unstable, mainly due to increasing moisture at lower levels[25]. Hail-favouring environments in reanalyses for the past 30–60 years have become 10–30% more likely over large parts of southern and central Europe, including southern France[109], Italy[114], northern Switzerland[26], Germany[99] and the Iberian Peninsula[115].

According to an additive regressive model applied to determine the frequency of severe-hail conditions over the whole of Europe (1979–2016), the largest increases with trends of +0.3–0.6 cases per year are in Switzerland, northern Italy, Austria and the Balkans; trends are not statistically significant over most of France and Spain; and the only negative trends are in areas of southeastern Spain and southern France[27]. The positive trends are primarily related to increases in convective instability[27]. Over a longer period of 60 years (1951–2010), an index quantifying the hail potential showed no statistically significant trends in most parts of Europe, with the exception of decreases in a few regions in the east, with the lack of significance attributed to the large annual and multiannual variability of the proxy[116].

Future projections. Studies that use proxies to identify future environments favourable for hail in Europe mostly project a (slight) increase in hail likelihood[63,99,112,114]. For example, an ensemble of 14 regional climate models (RCMs) shows environmental conditions conducive to severe hail becoming 40–80% more likely across large parts of Europe by the end of the century in a high-emissions scenario[63]. Moreover, the likelihood of very large hailstones is estimated to double over parts of central and northern Europe by 2100 (REF.[63]). However, depending on the period considered (before or after 2050) and the underlying climate simulation (emissions scenario), the simulations show different and partly contradictory results. High annual variability and ensemble spread often lead to very slight increases or little statistical significance in the results, especially for the near future to 2050 (REFS[99,112,114]).

In Germany, RCMs project, on average, positive trends in the frequency of hail-favouring weather types and hail potential for the mid-century[99,112]. For example, an ensemble of seven RCMs, showing high variability between the simulations, projects an increase in hail likelihood of 10–41% for the near future[112]. In Italy (2004–2040), one coarse-resolution global-climate simulation projects an increase in hail frequency for spring, summer and autumn[114]. An economic model based on the relationships between monthly hail insurance-loss data for agriculture and various temperature and precipitation indicators for the Netherlands projects that annual hail

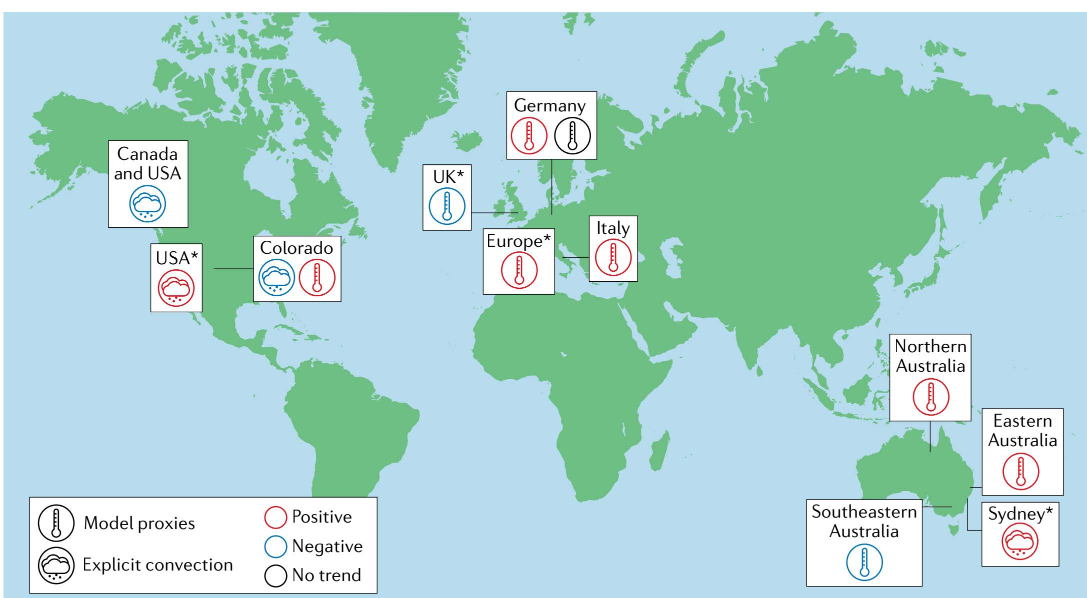

Fig. 4 | **Overview of future simulation studies and their conclusions on hail-frequency trends.** More high-resolution studies are required to understand climate change effects on hailstorms. Trend directions are for surface hail and geographic positions are approximate. An increase in hail-prone environments is interpreted here to indicate an increase in frequency. An asterisk indicates that the conclusions are for severe or larger hail. See Table 2 in the Supplementary Information for further details of the studies and the references.

Box 1 | Observing or inferring hail trends

Hail is a small-scale phenomenon[150] that occurs only rarely at any location[85,94,151] (FIG. 2), making it hard to observe and model. It is difficult to measure hail: human observations of hail size are often quantized or inaccurate[12], meteorological station reports are inconsistent[119,121,152] and reports from the media or public suffer from non-meteorological biases[10,121,152–156]. Hailpads, which record hailstone hits[157], measure hail size as well as frequency, but require manual maintenance and have low temporal resolution. Moreover, point measurements such as these lack spatial coverage and are statistically unlikely to sample the largest hail[158]. Indirect observation methods, which provide greater geographical coverage, include the use of radar[124,125,151,159,160], satellite[84,161] and insurance-loss[8,24,26,110,111] data to provide empirically calibrated estimates of hail size or occurrence probability, with associated uncertainties. However, remotely sensed time series are usually too short to estimate climatological trends[84], while insurance-loss data are restricted to unevenly distributed insured objects, the vulnerabilities and number of which vary in time[160], thus requiring careful treatment to extract meaningful signals[162]. Hail-suppression measures may also confound long-term observations[97,103,105,163–165].

An alternative to direct and indirect measurements is to study atmospheric 'ingredients' for hail-prone storms, primarily convective instability and low-level moisture availability[166,167] and wind shear[31]. Initial lifting of air parcels is also key[166,167], but often not addressed. The relative importance of ingredients varies geographically and between storms[16,59], and how best to form 'hail proxies' to identify hail-favouring conditions is an active research subject[16,27,31,48,112,126,145,168]. Proxies typically estimate only hail occurrence, because observations of other hail properties are rarely available for proxy derivation. Proxy studies draw conclusions about the environmental boundary conditions required for hail, but suffer from the 'initiation problem', in that they cannot determine whether hailstorms actually form. Even in hail-favouring conditions, it is rare that hailstorms occur[10,35].

High-resolution, convection-permitting simulations[28,169–171] that explicitly model hail[21,28,136] address the initiation problem. Nominally, a horizontal grid spacing of ≤4 km is required to resolve convective storm features[169,172,173], which is computationally demanding[4]. At coarse resolution, convection is parameterized and hail-favouring environments studied through proxies[15,17,63,99,112,135,137]; the initiation problem can then be addressed by using hail-growth models[22,47,168] or estimating hail occurrence given storm initiation[27]. Storm modelling is further complicated by the parameterization of microphysical processes[79] and high model sensitivity to initial values[174] and atmospheric environments[58].

Identifying hail trends and attributing them to climate change or natural long-term variability[152] requires sufficiently long time series. Proxy-based trend analysis is complicated by temporal[175] or spatial non-stationarities in the proxy relationships[59,147] that could mean that climate change affects the relationships themselves[176]. Hail observation and modelling are discussed further elsewhere[6,39,94].

damage in outdoor farming could increase by 25–48% by 2050 compared with 1990 (REF.[111]). By contrast, for the United Kingdom (1971–2099), a single RCM estimates negative trends in the number of damaging hailstorms[117].

Expected future changes to hailstorms in Europe are primarily attributed to an increase in convective instability resulting from greater low-level and mid-level atmospheric moisture content[63,112,114]. The projected decrease in hail frequency in the United Kingdom is, likewise, attributed to decreases in the climate model's convective instability proxy[117]. In the Atlantic region of France, increasing MLH is projected to shift hailstones towards larger sizes, reducing hailstone numbers but increasing hail intensity and causing hail to more or less disappear in regions where hailstones are usually small[29].

North America

Past trends. Long-term (1896–1995) records of hail days, based on visual observations of hail by trained weather observers at coarsely spaced (~100 km) weather stations in the USA, exhibit positive linear trends in hail-day frequency in the High Plains, central Rockies and southeastern regions, but their exact magnitudes are not specified[118]. These records show negative or no trends elsewhere in the USA[118]. A 17-year record (1977–1993) from Canadian hail-observing stations shows a positive trend in the average number of station hail days over Alberta, reflecting a doubling to 1.25 days per year, but no statistically significant trends elsewhere in Canada[119]. Analysis over a 24-year period (1979–2002) also shows a doubling in frequency of severe hail in Ontario, partly attributable to increasing report frequency[120]. Several studies show that numbers of public and media hail reports in the USA have doubled over the past three decades[10,12,121,122], but this increase is generally considered to be an artefact of easier reporting and population growth, rather than a meteorological effect[12,121]. Similarly, a trend towards larger maximum hail size in the southeast of the USA is attributed to the increase in hail reporting[12]. The number of US hail days in spring (April–June) over 1990–2013 displays no trend[122].

Other data have also been exploited to look for a historical trend in the USA. Analyses of insurance claims show conflicting results: national increases in hail losses[11] but slight downward trends in property-hail and crop-hail losses[123], although significance levels were not reported in either case. Weather radar data are not susceptible to the types of biases found in insurance claims and reports, but their limited record lengths result in uncertainties in trends. Nevertheless, the radar-based product maximum expected size of hail[124] was used to quantify characteristics of hail swaths (2000–2011)[125]. This analysis reveals a non-statistically significant negative trend in days with hail with diameters of at least 0.75 inches (1.905 cm), which is limited to the cold season, and a positive trend in large geographical areas affected by such hail, limited to the warm season[125].

Also using the maximum expected size of hail metric, the longer record of 1995–2016 reveals an increase in the area of events with very large hailstones over the USA, particularly associated with increases over the Great Plains and Midwest regions (statistical significance unstated)[77]. Corroborating this result are trends in environmental proxies computed from reanalyses (1979–2017) that show increases in the annual number of days with environments for very large hail of 2–4 days per decade in the Midwest[77]. There is some uncertainty in this proxy-based approach, as, without a metric for convection initiation or accounting for the large changes in CIN, changes to frequency may be overestimated[18,75]. A statistical-model-based approach in which hail occurrence is related to large-scale environmental proxies, including convective precipitation, shows no trend in frequency across the continental USA (1979–2012), but did not consider these trends regionally[126]. Overall, no clear overarching national climatological hail trend has been found for the USA[10,75,121,126], although recent evidence suggests the existence of regional positive trends in the frequency of very large hail[77].

Future projections. Future projections of North American hail intensity and frequency are generally consistent across various climate-modelling approaches. The suggestion from proxy-based studies is of an increase in the number of days favouring severe convective storms within most regions and during most seasons, with projected increases in convective instability outweighing the coincident decrease in mean vertical wind shear[14,17,28,64]. Specific information about changes in hail frequency, size and damage potential has been obtained through a novel application of a 1D hail-growth model, HAILCAST[22,47], at individual grid columns of RCMs conducted over historical (1971–2000) and projected future (2041–2070) time intervals[22]. HAILCAST was run for March–September, the most hail-prone months in North America[22].

Over a large area of North America, this modelling approach projects a decrease in the number of days with small (1-cm) hail in future springs and summers[22]. Specific decreases of ~1–2 days (~5 days) per season are indicated in the southeast USA (southern Rocky Mountains) during spring (summer)[22]. However, increases of several days in the frequency of small-hail days are projected for the Canadian Rockies and parts of the Northern Plains in the USA[22]. Similar increases and decreases are indicated for the frequency of severe hail days[22]. The Rocky Mountains and Northern Plains are also expected to experience increases in the frequency of hail of at least 4 cm (REF.[22]). The general conclusion is that drier and cooler regions in North America will experience the largest increases in hail threat, while warmer and more humid regions will experience a reduced threat[22]. These decreases in hail threat are due to increases in hail melt aloft rather than to decreases in hail generation[22]. Although HAILCAST can capture changes to CIN, as it implicitly decreases the likelihood of deep convective initiation with increasing CIN, it does not account for the presence of triggering mechanisms, in contrast to traditional modelling approaches.

Projections of hail proxies to the end of the century show an increase of up to three hail days per year in Colorado, which, when combined with population projections, implies a 178% amplification of human hailstorm exposure[127]. Convection-permitting simulations for past (1971–2000) and future (2041–2070) periods over Colorado reveal an increase in future hail generation in that area[21]. However, owing to increased MLH, most of the hail is projected to melt before reaching the surface, increasing surface rainfall[21]. Modelled melting processes are dependent on microphysics parameterizations, and the most damaging larger hailstones may be minimally affected by increased melting[21]. In contrast to this explicit-convection study, in which only select events were simulated[21], another study used a dynamic downscaling approach to compare year-round simulations of 1971–2000 to 2071–2100 at convection-permitting 4-km resolution for the USA[28].

With the dynamic downscaling approach, the frequency of large hail is predicted to increase in all seasons, the frequency of very large hail is predicted to increase in spring and summer in the central USA and the frequency of severe hail is predicted to decrease across the eastern half of the country in summer[28]. Across the whole year, an increase in the number of hail days is predicted, with increases of 7%, 21% and 146% for severe, large and very large hail, respectively, with an associated increase in the length of the hail season[28]. In summer, however, the results suggest a trend towards fewer hail events but larger hail, as also predicted by HAILCAST simulations[22]. The increases in large and very large hail are attributed to wider and more intense updraughts in the future scenario and the decreases in severe hail over the eastern USA in summer to reduced numbers of convective storms[28].

South America

Despite the severity of convection in subtropical South America[84,128], ground-based radar data and long-term continuous observational station records are extremely limited across the continent. Thus, studies on the effects of climate change on hail frequency or associated environments are comparatively rare over South America[129–131]. Reported trends in hail frequency (1960–2008) vary by region, with a negative trend in central and eastern Argentina that results in a 30% reduction in the number of events, no statistically significant trends in Cuyo and Patagonia, and modestly positive trends ($P = 0.1$) in the northwestern and northeastern regions[129]. In Argentina, there is, thus, an apparent ordering of the trends by latitudinal bands, with positive trends in the north and both statistically significant and non-significant negative trends between 30 and 45°S (REF.[129]).

A time series of annual numbers of hail days near Mendoza in the Andes displays similar oscillations to those in a series of global annual mean surface temperature[132], although there are discontinuities in the hail-observation record that preclude analysis of long-term trends. Over the border region between Brazil and Argentina (1956–2016), only three of 21 stations show statistically significant trends in hail days, with two significantly negative and one modestly positive[131]. Tying these signals to the synoptic environment, there is a negative trend in the temperature difference between the 925-hPa and 250-hPa vertical levels, which is consistent with the observed reduction in hail frequency in some regions[129]. There have been no studies of future projections of hail or the storms that produce it over South America.

Oceania

Past trends. Studies on hail trends in Oceania have been limited to Australia. The Australian Bureau of Meteorology maintains an archive of severe-storm observations, and, although it is an imperfect record[13], it has been used to examine hail trends. Analysis of collated hail reports for New South Wales show that hail frequency was lower in 1989–2002 than in 1953–1988 (REF.[133]). There is a decrease in hail frequency since 2009 in extracted reports of severe hail from 1989 to 2013 for the region surrounding Sydney; however, the statistical significance of this trend is unclear[134]. Comparatively little attention has been paid to past long-term changes in hail-favourable environments. Trends in vertical wind shear are not an important factor for crop-hail losses in this region[76], and long-term trends in the product of convective available potential energy (CAPE) and wind shear from reanalysis data are not statistically significant over the Australian continent or its east coast[56].

Future projections. An early analysis used hail-loss model projections for winter crops in two locations in New South Wales, Australia[76]. These hail-loss models were applied to three coarse global models with doubled CO_2 scenarios applied to a reference climatology between 1969 and 1978 and show non-statistically significant decreases[76]. A study of CAPE, which measures atmospheric instability, and hail incidence for 1980–2001 at two stations in southeastern Australia in a similar doubled CO_2 scenario shows that the mean CAPE decreases by 10%, which was inferred to mean decreases to hail frequency despite proxy results not being statistically significant[135]. Both of these studies assessed changes using coarse-resolution data from a climate model that seemed to show anomalous decreases relative to subsequent analyses[65,66]. More recent projections of future changes in hail over Australia are less certain. A six-member ensemble of climate projections for the Sydney Basin shows large inter-decadal variability and no long-term trends in hail frequency or hailstone size in a no-warming scenario for the mid-twenty-first century[136]. However, in a climate change scenario, return intervals for hail exceeding 10 cm almost halved from 52 to 28 years[136].

For severe hail, there are more hail events per decade in the climate change scenario, resulting in a 40% relative increase in hail frequency and a greater number of intense events (statistical significance unstated)[136]. These changes are attributed to increased surface temperatures and dew points sourced from the nearby warming ocean, leading to an increase in convective instability and intensity of sea-breeze circulations driving storm forcing[136]. These results are consistent with the 20–30% increases in severe-thunderstorm environments over eastern Australia by the end of the twenty-first century that are projected by simulations[65], which show decreases in the occurrence of high vertical wind shear that are not strong enough to offset increases in convective instability when low-level moisture is available[65]. Results showing an increase in future hail potential in Australia contrast with those from an earlier study[135], possibly owing to differences in the capacity of the horizontal and vertical resolution of climate models to resolve changes to convective environments[16], as well as unusual biases within the model used in the earlier study[65,137].

Summary and future perspectives

Climate change is likely to affect hailstorm frequency in many parts of the world. Observed trends and modelled projections together give overall indications that hail frequency will decrease in East Asia and the USA, slightly increase in Europe and increase in Australia (TABLE 1). In several regions, there are indications of a shift towards increasing hail severity, even with decreasing hail occurrence, owing to the combined effects of increasing convective instability and an increasing MLH. However, key hail-forming processes within thunderstorms are still only partially understood, and uncertainties are, therefore, large[58]. Inter-study comparisons are difficult, owing to the use of varying time periods, measurement techniques, future scenarios or model configurations. Although changes to hailstorms and hail properties are clearly observed and projected in some regions, dedicated attribution studies are required to definitively link specific changes to anthropogenic climate change. The global picture of how hailstorms will be affected by climate change in the future remains unclear, with many unstudied regions, a lack of long-term observational data, gaps in process-level understanding complicated by interactions between hail-relevant atmospheric variables and limited hail modelling. Accordingly, we make five recommendations for future studies.

First, improved observational records of hail are required, including long and homogeneous data sets to enable separation of natural climate variability from potential trends due to anthropogenic climate change.

Table 1 | **Summary of past trends and projected future changes to hailstorms and relevant atmospheric changes by region**

Region	Observed trends	Projected future changes	Relevant changes
East Asia	Decrease in hail frequency[20,74]; decrease in annual maximum hail size[90]; decrease in mean severe hail size[89]	–	Increasing convective instability[20]; increasing MLH[20]; decreasing low-level moisture[87]; increasing aerosols[20]; increasing convective inhibition[74]
Europe	Little agreement in observational trends[48,105,107]; increase in damage[24,48]; increase in intensity[48,105]; moderate increase in hail-favouring environments[99,109]	Slight increase in environments[63]; low significance, some contradictions[99,112,114]	Increasing convective instability due to increasing low-level moisture[63,112]; increasing MLH[110,115]
North America	No clear overarching observational trend[118,122]; no clear overarching environment trend[10,75,121,126]; regional trends in very-large-hail environments[77]	Increase in environments[14,17,28,64]; during warm season, decrease in severity in warm and humid regions, increase in severity in dry and cool regions[22] and fewer but severer events[28]; year-round increase in severe-hail frequency and shift to larger hail[28]	Increasing convective instability[17]; increasing convective inhibition[75]; decreasing vertical wind shear[17]; increasing MLH[21]
Oceania (Australia)	Possible decrease in frequency[133,134]	Increase in frequency[136]; increase in severity[136]; increase in environments[65]; large inter-decadal variability[136] and studies disagree[135]	Increasing surface temperature[136]; increasing convective instability[65,136]; not all studies in agreement[135]

References are selected examples; please see the main text and the Supplementary Information for complete references and more specific results. Limited data availability and high regional variability in known hail trends in Africa[27] and South America[129,131] preclude their inclusion in this table. No future hail projections are available for East Asia. MLH, melting level height.

When possible, observations should include both hail frequency and hailstone size. Although longer time series are required in all regions, there is a particular need for observations in hailstorm-prone locations outside of North America and Europe, such as in tropical, northern and southeastern Africa; the southwest of the Arabian Peninsula; the Hindu Kush; the north and far east of India; the north of Laos; Australia's east coast; and northeastern Argentina[85] (FIG. 2). Given the practical limitations in deploying and maintaining long-term instrument networks, methods for remotely sensed hail detection should continue to be improved while maintaining the required ground validation. The best solution would be large, long-term hailpad or hail disdrometer networks; however, the inadequate monitoring of hail can be partially remedied by additionally considering data from crowdsourcing, civic science contributions and historical data retrieval, including quantitative and qualitative hail-loss information.

Second, statistical proxy relationships between environmental conditions and hail occurrence must be evaluated and improved. Proxy studies are extremely valuable, but current relationships typically cannot account for hailstorm initiation. Furthermore, the implicit assumption that the statistical links will remain stationary in a warmer climate may be questionable[18]. For example, positive correlations between hail occurrence and local surface temperatures may be affected by future soil moisture changes[138] and associated changes to CIN[139], and changes to the hail-size distribution may alter supercell storm structures[83]. These statistical links need to be tested in hail-resolving model simulations to detect possible future changes. Alternatively, machine learning approaches that allow for non-stationarity could be considered[140,141].

Third, an emphasis on process-oriented studies is required. There is wide variability in trends and projections for hail, and even studies in the same region have reached opposing conclusions. To untangle how climate change may affect hailstorms, and to better compare studies, observed changes in environmental conditions must be tied to their effects on hail through detailed studies of the microphysical chain of events leading to hail production within the storm and the hail that ultimately falls to the ground. Environmental conditions and atmospheric processes not only influence hail trends caused by climate change but also the annual variability in hailstorms, which can be larger than the estimated trends[116,126]. Process interactions cannot be ignored. For example, convective instability and vertical wind shear both contribute to hailstorms, and, even if their separate trends show little change or decreases in storm-favourable values, it is possible that the frequency with which they are simultaneously favourable for hail may increase and lead to overall increases in storm environments[67]. It is also necessary to understand the connections between dynamic processes on the synoptic and climate scales as they relate to hail. For example, several studies have highlighted teleconnections, or long-distance links, to climate variability[6,122,142–144]. Similar investigations have shown relationships to weather regimes[99] and the location of the jet stream[65,87].

Processes relating to low-level moisture and convective instability, microphysics and storm initiation should be a particular focus of investigation. In this regard, improved modelling of low-level humidification of the atmosphere is required[57], and regional variability in the utility of different instability metrics means that a variety of indices should be considered[4,56,135,145]. Field experiments and simulations should be used to further understanding of fundamental microphysical processes. To this end, dedicated field programmes should be designed to address knowledge gaps in hail processes. The relative importance of embryo (and INP) concentration[58,146] versus overall storm dynamics and embryo trajectories[31] on the hailstone-size distribution should also be investigated. In numerical modelling, properties of the hailstorms produced are sensitive to microphysical parameters, such as the fall speed of ice particles, and environmental conditions, such as vertical wind shear[58]. It is necessary to determine whether microphysical details of hail initiation and growth must be considered or if environmental factors alone are sufficient for skilful surface-hail projections. Finally, possible changes to storm initiation also demand further study, as differences in initiation frequency may partially explain disparities between European and North American severe-storm observations[147] and trends[75], and large-scale changes in synoptic circulation and related lifting can affect convective activity[99,115,136]. Changes in severe-thunderstorm environments may overestimate changes in hail occurrence[18,75], and, thus, explicit estimation of the likelihood of storm initiation is useful[27].

Fourth, changes to hail damage and its economic impact require deeper investigation, with attention not only on hail properties but also on changes to hail exposure and vulnerability. Crop vulnerability, for example, depends on species and plant growth state[8,148], the cycle of which may alter owing to climate change. Solar panels, which may be increasingly used in future, are also particularly vulnerable to hail damage[149]. Possible investigation approaches include coupling convection-resolving simulations to impact models and projections of future population growth[127], and the use of statistical tools that can deal with non-stationarities in relationships between hazard, exposure, vulnerability and climate change[141]. Future studies should also include modelling of the potential future economic impact of hail.

Fifth, and finally, more high-resolution numerical model simulations are required to better resolve hailstorm processes and to investigate expected future changes around the globe. As computational power increases, it will be possible to run convection-resolving simulations over larger regions and for longer time periods at increasing resolution and in ensemble modes.

Hailstorms regularly cause substantial damage to agriculture, human assets and infrastructure across the globe. Understanding of how hailstorm frequency and intensity will change in a warming climate is still limited, but concerted scientific effort focusing on the points above has the potential to close this knowledge gap.

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O.M. initiated the project and assembled the authorship team. T.H.R. led the project, researched the data and drafted the manuscript and original figures. All authors contributed to writing and editing of the manuscript prior to submission.

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