DISSERTATION

PROJECTING END-OF-CENTURY HUMAN EXPOSURE TO EASTERN COLORADO

TORNADOES AND HAILSTORMS: METEOROLOGICAL AND SOCIETAL PERSPECTIVES

Submitted by

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ABSTRACT

A SYNTHESIS OF METEOROLOGICAL AND HUMAN FACTORS INFLUENCING EASTERN

COLORADO SEVERE HAIL AND TORNADO LANDSCAPES

The eastern half of Colorado is one of the most active areas for hailstorms and

tornadoes in the U.S. An average of 39 tornadoes and 387 severe hail reports are tallied

each year over this domain, and a number of damaging events, particularly hailstorms,

have occurred in recent years. In an era of climate change, it is of worth to project how the

frequency, geography, and severity of tornadoes and hailstorms may change over time, and

doing so on a localized scale can shed light on the small-scale complexities that broader

analyses miss. It is important to consider both meteorological and non-meteorological

effects when projecting the changing human risk and exposure to these hazards in the

future, as human factors such as population growth means that more people may

potentially be exposed to tornadoes and hailstorms regardless of how climate change may

influence storm characteristics. As such, this doctoral study employs a multidisciplinary,

multi-perspective approach to investigate how the tornado and severe hail footprint may

change across eastern Colorado by the end of the 21st century, and in turn how the impacts

on those who live and work in this area may be exacerbated.

A baseline climatology of tornadoes and hailstorms across eastern Colorado is

established using Storm Prediction Center data records. Both hazards show increasing

frequency since the 1950s, but when the temporal range is limited to 1997–2017, tornado

reports and days show decreasing trends while severe hail reports and days continue to show upward trends. Population bias is inherent in the data records of both hazards and manifests itself as a clustering of reports near urban centers and along major roadways where people live and travel. However, the increasing number of severe hail days and proportion of hail reported at larger sizes is less likely to be influenced by population growth and thus may have a meteorological origin. Convective parameters output from high-resolution dynamical downscaling simulations of control and future climate scenarios using the Weather and Forecasting model are used as proxies to create and compare synthetic tornado and hail reports between the two simulations. Up to three more severe hail days and one more tornado day per year on average by the period 2071–2100 is found, maximized in the north-central part of the domain. This result is combined with population projections from the Shared Socioeconomic Pathways in Tornado and Hail Monte Carlo models to simulate changes in the number of people living underneath tornado tracks and hail swaths by the year 2100. Human exposure evolution is sensitive to the overlap of population and hazard spatial footprints, but the model predicts worst-case scenarios of a 178% increase in exposure to severe hail and a 173% increase in exposure to tornadoes by the end of the 21st century. In addition, population effects outweigh meteorological effects when simulated independently. Some simulations yield a decreasing human exposure to severe hail due to the greatest projected increases in hailstorms over rural, agricultural land. This finding provides motivation for an interview study of eastern Colorado farmers and ranchers to measure perceptions of exposure and sensitivity to severe hail. Most interviewees view hailstorms as a common nuisance throughout eastern Colorado and are most concerned with small hail that falls in large volumes or is driven by

a strong wind since these scenarios cause the most damage to crops. Respondents express anxiety and dejection toward hailstorms, as they can significantly affect crop yields and in turn impact their livelihoods and local economy. Understanding this agricultural perspective validates ongoing research into hail surface characteristics and can promote stronger partnerships between the forecasting and farming communities. The synthesis of results from this dissertation, with its unique localized look at the human and meteorological factors contributing to a changing exposure, can be of great worth to forecasters, urban planners, emergency managers, insurance agents, and other local decision-makers. Moreover, this work will help to educate the local public about the past, present, and future of tornadoes and severe hailstorms within eastern Colorado, with the aim of protecting lives and property from their negative impacts.

ACKNOWLEDGMENTS

Coming to the end of my doctoral journey at Colorado State University feels a little bit like the climate of eastern Colorado. Roughly 80% of the time I have been blessed with sunny days in the research world, making new revelations, producing instructive plots, or sharing my work with various groups within the community. There have been a few times in which a summertime hailstorm or wintertime blizzard has impacted progress, which temporarily caused stress or head scratching over some unforeseen result or mistake in the methodology that required deeper thinking. And every once in a while, there has been a stubborn wave cloud in the form of a glitch in a code that takes most of the day to erode. My aim to maintain a pleasant outlook in both sunny days and storms has culminated in what I believe to be an enlightening and impactful doctoral dissertation and related publications. I owe great thanks and appreciation to a large number of people for their contributions and support of this work, whom I will acknowledge now.

I first and foremost want to give praise and glory for the completion of my doctoral studies to God, who has consistently given His favor and grace to persevere and strength to complete the tasks asked of me. I pray that He would use this work to help improve the lives of others and point to His complex governing power of the atmosphere.

My Ph.D. committee has been instrumental in encouraging and aiding me in the research endeavors, each with his or her own unique contributions. Dr. Russ Schumacher has advised me for almost five years, and his support and interest in my work is unmatched. Even when I have wanted to pursue topics that broaden the research group's

scope, Russ has encouraged me to forge ahead and has suggested new ideas or areas to investigate. His support for me at conferences and workshops has been greatly appreciated and has increased my self-confidence as both a researcher and educator. More than just a mentor, Russ has modeled what it means to produce high-quality work while maintaining a healthy work-life balance. As I prepare for my entrance into the "real world," I look to Russ as an example of the cordial, supportive, and humble professor I hope to become. Drs. Kristen Rasmussen and Steve Rutledge have also been a part of both my Master's and Ph.D. pursuits, and are always happy to answer questions and discuss research updates. Kristen has played an integral role in the pseudo-global warming analysis by supplying data and helping interpret results, and her 2017 manuscript provided motivation for a key part of Chapter 4. Steve's thoughtful questions throughout the past few years have prompted additional literature review and critical thinking, particularly as it relates to hailstorm environments across eastern Colorado. Dr. Julie Demuth was incredibly helpful in providing expertise and guidance on the social science applications presented in Chapter 5. Her encouragement and feedback have been uplifting and confidence-building, and I have gleaned much wisdom about how to navigate the waters of interdisciplinary science. I also acknowledge my fifth committee member, Dr. Dennis Ojima, who provided constructive feedback on my interview protocol and how to engage the agricultural community, as well as original committee member, Dr. Craig Trumbo, for providing risk analysis expertise.

The Department of Atmospheric Science at CSU has been a welcoming and delightful place to work. From the office staff who create a positive and nurturing environment for students, to the many professors from whom I have learned much science through classes

Ernest Agee from Purdue University. Some eight years ago he offered me an undergraduate research position – to which I hesitantly accepted – and thereby put me on the track to achieving this doctorate degree. He is a dear friend who continues to provide input and support for my work.

My mom and dad have walked alongside me for my entire educational path, and while they are probably happy that I am finally done with school, their love and support have been so encouraging and motivating to press on toward the goal. My sister Sarah has also played a big role in reminding me to relax and enjoy each new day. My wife Swae has witnessed my Ph.D. journey more than anyone, and she has taught me how to believe in myself, foster principles for success and leadership, and remain grounded in my faith that God is working out all things for my good and His glory.

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CHAPTER 1: INTRODUCTION

As light began to penetrate anew through the windows of the Cheyenne Mountain Zoo in Colorado Springs, Colorado on the afternoon of 13 August 2018, anxious zoogoers quickly realized they had ridden out one of the most impactful hailstorms in Colorado state history. A short walk from the zoo grounds to the parking lot revealed some 500 vehicles that would be rendered undriveable due to the incredible amount of hail damage. This event, which resulted in five animal fatalities and at least a dozen human injuries – the second highest documented injury total of any Colorado hailstorm since the 1950s – not only attracted much media attention but was noteworthy for its applicability to multiple spheres of influence and expertise. Understandably, the aftermath of the Cheyenne Mountain Zoo incident provoked a number of questions: Why was this hailstorm so damaging? Are hailstorms like this going to become more common? What can be done to improve risk communication in an event like this? What mitigation strategies can be employed to prevent similar destruction in the future? Providing answers to these multifaceted questions is not an easy task, but are worth investigating for their pertinacity to today's ever-changing meteorological and social environments. As such, the aim of this interdisciplinary doctoral study is to investigate current and future landscapes of severe convective hazards, namely hailstorms and tornadoes, and their associated human exposure and vulnerabilities, for the domain space of eastern Colorado. In addition to providing valuable results for the meteorological, agricultural, and other decision-making sectors, this study will also reveal the importance of integrating physical science with social science to provide a more complete picture of the research problem at hand. Such an

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approach is considered by many to be the way forward in the atmospheric science field (Demuth et al. 2007, Morss et al. 2011, NAS 2018, Childs et al. 2019), and although challenging to implement, strategies utilized in this doctoral study provide one example of a successful integration of these disciplines. This opening chapter will set the stage for the research effort by providing a synthesis of background information on hailstorms and tornadoes and the societal components governing potential human exposure in context of the meteorological intricacies and human lifestyle divides evident across the domain space of eastern Colorado.

A. Colorado Severe Weather Landscape

Severe thunderstorms, particularly those which produce tornadoes and severe hail, pose a serious societal risk throughout much of the United States. An average of 1200 tornadoes occur across the U.S. each year, some of which cause human casualties and leave behind a trail of destruction (NSSL 2017). Hailstorms are also a ubiquitous feature of spring and summer U.S. weather, and while they rarely induce human injuries, large hail routinely damages automobiles and buildings and razes crops. While severe weather can happen anywhere in the United States, the majority of severe events occur east of the Rocky Mountains. Here, the roles of topography, upper-level flow patterns, and moisture transport via the low-level jet into a relatively cool and dry continental air mass help provide vertical instability and other ingredients needed for convection (Doswell 1980, Brooks et al. 2003b). While some of the most extreme severe weather events have occurred well downstream of the Rocky Mountains, the area in its immediate lee across eastern Colorado has experienced several high-impact events in recent years (e.g., Schumacher et al. 2010, Hamill 2014, Childs and Schumacher 2018) and is a worthy

domain across which to analyze and project severe weather events and their associated societal impacts. For reference, Fig. 1.1 displays a state map of Colorado showing counties and select cities and roadways, many of which will be referenced throughout this and the following chapters.

The influence of the Rocky Mountains on Colorado severe weather is undeniable and has been the subject of myriad field projects and research studies. Whereas severe weather across the South, Midwest, and eastern United States is dependent upon high values of Convective Available Potential Energy (CAPE) and storm-relative vertical wind speed shear (Brooks et al. 2003b, Tippett et al. 2014, Allen et al. 2015a, Tippett et al. 2015), eastern Colorado severe weather environments typically have lower CAPE and speed shear and are characterized by an anomalously moist boundary layer and very strong storm-relative directional wind shear (Doswell 1980, Maddox et al. 1981, Szoke et al. 1984). Two mesoscale features that aid in the formation of intense convection across Colorado and the adjacent High Plains region despite relatively low CAPE and wind shear were discovered and formally defined during the 1980s decade as a result of multiple field projects, including the Joint Airport Weather Studies (JAWS; McCarthy et al. 1992) and the Convective Initiation and Downburst Experiment (CINDE; Wilson et al. 1988). First, the Denver Convergence Vorticity Zone (DCVZ) is an area of converging winds that forms when two different air masses meet near metropolitan Denver. Warm and moist southeasterly flow ascends the Palmer Divide, a topographical feature of locally higher elevation between Colorado Springs and Denver, and converges with northwesterly flow moving downslope from the foothills to the north and west of Denver. This convergence leads to a localized
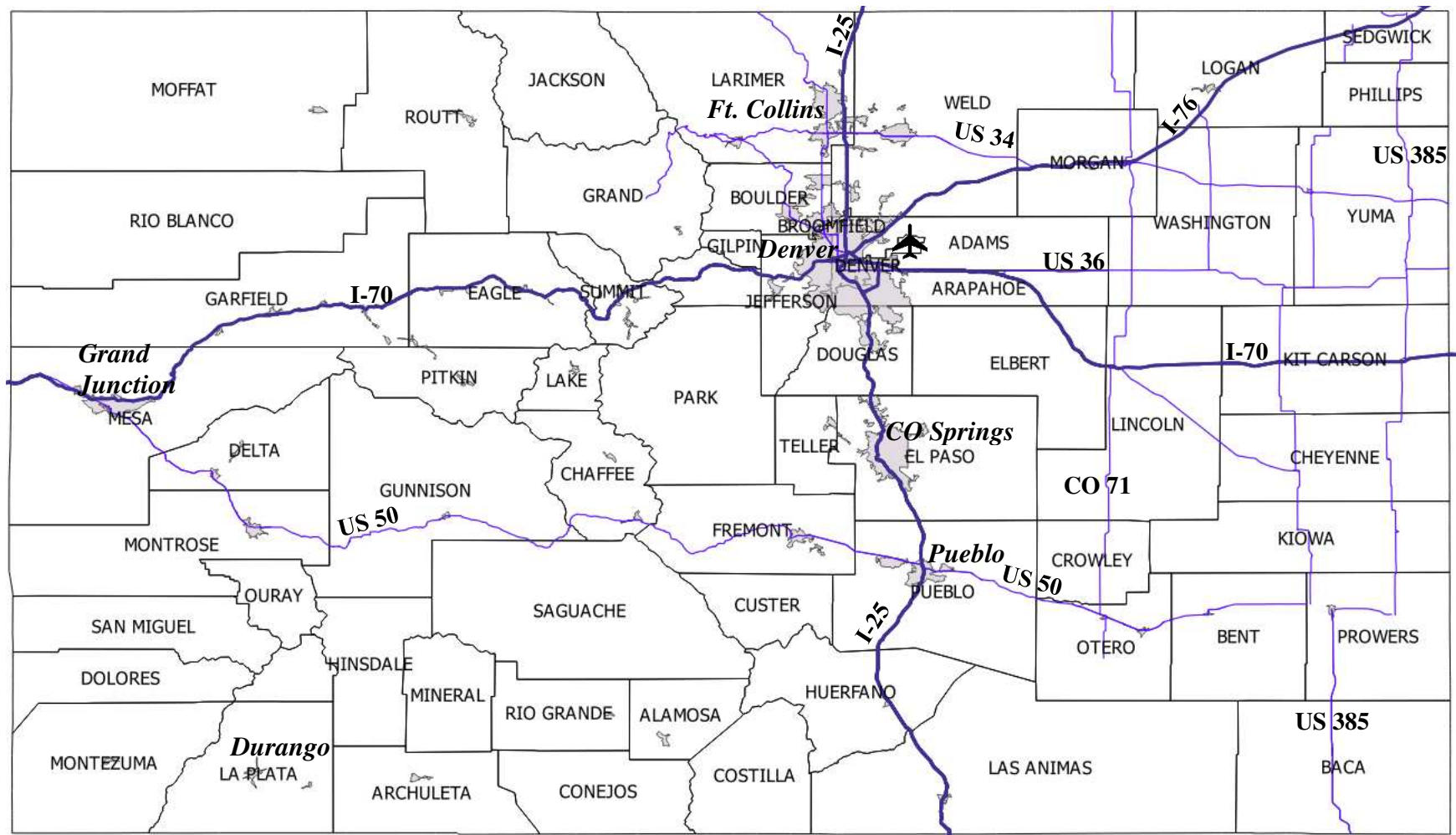
Fig. 1: State map of Colorado showing county names (uppercase), select cities (light gray shading and bold italic labels), Interstate Highways (thick blue), other primary roadways (thin blue), and Denver International Airport (black airplane symbol).

area of vorticity, now commonly known as the Denver Cyclone (Szoke et al. 1984, Crook et al. 1990). As low-level vorticity is a key ingredient for tornadogenesis (Markowski and Richardson 2011, Coffer et al. 2017), it is not surprising that the Denver Cyclone was observed on many severe weather days across the Front Range during the JAWS and CINDE field campaigns in the 1980s (Szoke et al. 1984, Wilson et al. 1988, Brady and Szoke 1989), and continues to be a frequent feature of Front Range summertime severe weather today. A third experiment of the 1980s was the 1985 Real-Time (RT85) convection forecasting exercise administered by the Program for Regional Observing and Forecasting Services (PROFS; Schultz et al. 1989). This campaign incorporated forecaster-generated convective outlooks as well as rawinsonde data to determine the most useful metrics for severe weather and significant weather across northeast Colorado. While buoyancy (e.g., CAPE) was one of the best discriminators, the SWEAT index, which was the only parameter analyzed that included a wind shear contribution, performed best, indicating the importance of strong wind shear in favoring severe weather in this part of the country.

Precipitable water, which is a measure of how much water is present in the atmosphere that could potentially precipitate out as rain or hydrometeors, was also found to be a useful parameter for severe weather events in the RT85 experiment. That enhanced moisture is a favorable ingredient for severe weather across eastern Colorado is particularly interesting given the dry, mountainous climate. The topographic complexities of the Rocky Mountains and adjacent foothills provide opportunities for elevated heat sources, which, when placed over a cooler surface, sets up a thermodynamic instability that when aided by an intrusion of moisture, can help trigger vigorous convection. This concept is related to the idea of "elevated mixed layers" (EMLs), which are layers of constant

potential temperature above the planetary boundary layer as a result of advection of relatively warmer air heated by surface terrain (Carlson et al. 1983, Ribiero and Bosart 2018). When EMLs lie above a cooler yet more moist boundary layer, potential instability increases, and if other factors can enable the penetration of the stable EML, high-impact weather can ensue downstream (Cordiera et al. 2017), including in the domain of interest across eastern Colorado. This idea can also be thought of as one example of an atmospheric capping inversion. The stable EML serves as a lid underneath which convection is prevented due to its characteristic temperature inversion, with temperatures increasing with height in the layer. Only when there is sufficient vertical motion of moisture-laden air will the cap break and allow for thunderstorms. To use a more tangible analogy, suppose a bag of uncooked popcorn is placed into a microwave. As the bag is warmed, it expands, and for a time forms cap that serves as a barrier to the kernels popping. However, once the pressure is sufficient to overcome the cap, the kernels burst and form the familiar popcorn shape. A stronger EML means that even greater amounts of positive buoyancy are needed to overcome the inversion; however, when this does occur, more intense convection is likely to ensue. As this is a common feature of the eastern Colorado warm season, Chapter 4 will explore projected changes in the convective population of this region based on positive and negative buoyancy in model simulations of control and future climates.

"Severe weather" is defined by the Storm Prediction Center (SPC) as an occurrence of any of the following: (a) a wind gust in excess of 58 mph, (b) hail of at least 1.0 in diameter, or (c) a tornado of any kind. Forecasters issue warnings based on these criteria, and cater their messages to the magnitude of the threat and potential impacts to humans and property. While the applicable domain of eastern Colorado experiences each of these

weather hazards, this study will focus specifically on those hazards that are attendant to convection, namely tornadoes and hailstorms. Severe winds certainly pose a threat in this region, although many severe wind events here are the result of downslope windstorms and not associated with warm-season convection, and severe wind data has only recently begun to be tested for validity in climatological and meteorological analysis (Edwards et al. 2018). A wealth of research exists that aims to analyze and model various facets of severe weather, such as storm structure, dynamics, and environments, as well as project future climate change impacts, many of which will be referenced herein. A brief overview of tornadoes and hailstorms is warranted before giving many more specific details of their regional climatologies in Chapter 2.

1. Tornadoes

Climatologically, tornadoes are most prevalent across the traditional "Tornado Alley" region of the U.S., which extends from roughly central Texas northward through Oklahoma, Kansas, and Nebraska (Gagan et al. 2010). This region arguably has the most favorable environmental setup for tornadogenesis, although it remains an open research question as to why some storms produce strong and violent tornadoes and others do not. Another maximum in tornado frequency is noted across the Southeast U.S. (Fig. 1.2, 1.4b; Gagan et al. 2010, Dixon et al. 2011), where a secondary tornado season in the cool season is often manifested (Guyer and Dean 2010, Childs et al. 2018). Much work has investigated the ideal environmental conditions for tornado activity, and in general a combination of enhanced vertical wind shear and sufficient thermodynamic instability are agreed upon as favorable tornado precursors (Rasmussen and Blanchard 1988, Brooks et al. 2003b, Thompson et al. 2012). Storm-relative helicity, a measure of the potential for cyclonic

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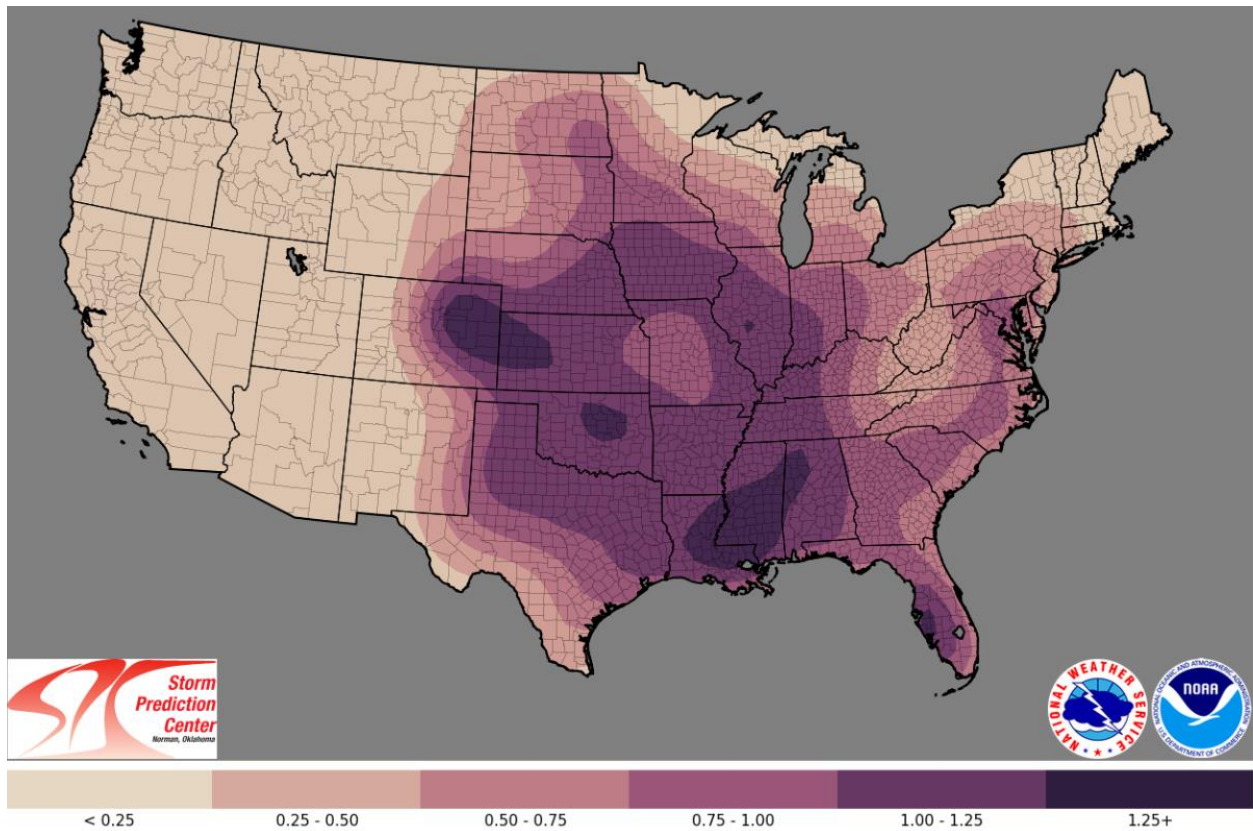
Fig. 1.2: Mean number of tornado days per year within 25 miles from a point for the period 1986-2015. Adopted from SPC WCM data sheet, available online at https://www.spc.noaa.gov/wcm

rotation of an updraft, as well as convective precipitation, have also been found to discriminate between tornado and non-tornado environments (Thompson et al. 2012, Tippett et al. 2014).

At smaller scales, tornadogenesis requires that vertical vorticity be found at the surface. When initially absent, vertical vorticity can reach the surface by tilting and stretching of antecedent horizontal vorticity (Markowski and Richardson 2011). Attendant downdrafts within the thunderstorm can then advect vertical vorticity downward to the surface as it is being stretched. Further, Coffer and Parker (2016) found in simulations of

tornadic and non-tornadic supercells that streamwise vorticity as opposed to crosswise

vorticity at low levels is more favorable in producing a stronger mesocyclone that ingests

and vertical motion that more vigorously stretches the horizontal vorticity to eventually

produce a tornado. The argument that downdrafts are essential for tornadogenesis if

surface vertical vorticity is initially absent also implies the presence of a strong

thunderstorm with appreciable updraft strength. Indeed, most tornadoes, especially

strong and damaging ones, are produced from supercell thunderstorms (Davies-Jones et al.

2001).

The Storm Prediction Center (SPC) maintains data records of U.S. tornadoes back to

1950. Over the entire period of record, tornado reports and tornado days are increasing
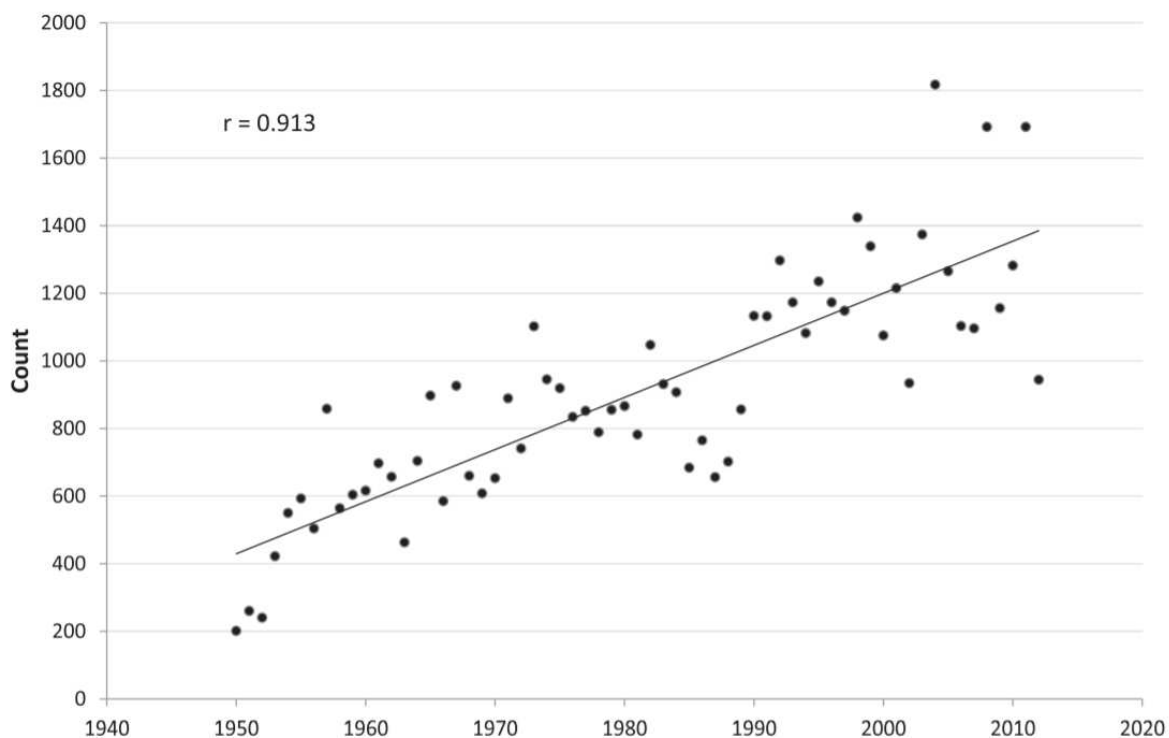
Fig. 1.3: Annual U.S. (E)F0-(E)F5 tornado count based on SPC storm reports for the period 1950-2012. Adopted from Agee and Childs (2014), their Fig. 1.

nationwide at all intensity thresholds (Fig. 1.3; Agee and Childs 2014). However, in the more recent period since 1997 when data records are considered to be more reliable (a topic to be explored in Chapter 2), there is essentially no trend in (E)F0-(E)F5 tornado reports, and significant tornadoes, (E)F2+, have a decreasing trend (Verbout et al. 2006). Despite the decreasing frequency, the number of tornadoes on tornado days (Elsner et al. 2015), tornado power and kinetic energy (Fricker et al. 2017, Elsner et al. 2019), tornado variability (Brooks et al. 2014), and tornado volatility (Tippett 2014) are increasing over time. The spatial distribution of tornadoes has also shown a notable eastward and southward shift in recent decades, away from the traditional "Tornado Alley" (Agee et al. 2016). Regional, seasonal tornado predictive power has been found in examining relationships with teleconnections such as the El Niño-Southern Oscillation (Cook and Schaefer 2007, Allen et al. 2018), North American low-level jet (Weaver et al. 2012), and the Arctic Oscillation (Childs et al. 2018). Seasonal-to-subseasonal probabilistic tornado prediction has also been performed using statistical models (Elsner et al. 2016), machine learning techniques (Cintineo et al. 2014, Baggett et al. 2018, Sandmael et al. 2020), and other indices (Gensini and Marinaro 2016, Gensini and Bravo de Guenni 2019). On shorter time scales, mesoanalysis, radar signatures, spotter networks, and storm chasers are used by the National Weather Service (NWS) and SPC to issue Tornado Watches and Tornado Warnings for imminent threats, although predicting the exact path and intensity of a tornado remains a forecasting and nowcasting challenge. Tornadoes are assigned an intensity rating hours to days after they occur based on the (Enhanced) Fujita-Scale, originally developed by "Mr. Tornado" Ted Fujita in 1971 (Fujita 1971). The modern EF-scale contains 28 damage indicators, and the tornado is assigned an intensity rating based

on the degree of damage produced to one of the indicators rather than on instantaneous wind speed. One consequence of this that has relevance to the domain space of eastern Colorado is that tornadoes traveling over barren or agricultural land are generally underestimated in their intensity due to a relative lack of structures to damage compared to those traversing across more urban areas (Strader et al. 2015).

Despite not being located in the traditional "Tornado Alley," eastern Colorado is actually a local hot spot for tornadoes, with several studies showing a relative maximum in tornado frequency across this area (e.g. Brooks et al. 2003a, Ashley 2007, Allen et al. 2015a, Farney and Dixon 2015). In fact, when tornadoes over the period 1950–2016 are considered, Weld County in northern Colorado ranks first out of all U.S. counties for most tornado segments passing through it. These results must be taken in context, however, noting that Colorado sees a much higher proportion of weak tornadoes and landspouts compared to other parts of the country. Landspouts by definition are a type of tornado because they are impingent on a cumuliform cloud, but are non-mesocyclonic in nature and do not require the presence of a downdraft. Landspouts most commonly form via stretching of preexisting vertical vorticity from a surface boundary or mesoscale eddy, in contrast to arising from a supercell with strong mid-level rotation (Markowski and Richardson 2011). In Colorado, the DCVZ is one such source of vertical vorticity that can frequently produce non-mesocyclonic tornadoes (Brady and Szoke 1989, Wakimoto and Wilson 1989). As a result of their tendency to be weak and short-lived, tornadoes in eastern Colorado have rarely resulted in human fatalities (Ashley 2007). Nevertheless, six tornadoes since 1997 have been assigned an (Enhanced) Fujita-Scale rating of (E)F3, and two of those – in the town of Holly in 2007 (The Denver Post 2007) and near Windsor in

2008 (NWS Boulder 2008) – resulted in at least one fatality. Tornadoes in the state of

Colorado are nearly all concentrated east of the foothills, but in rare cases can occur on the

Western Slope and in mountainous terrain. Of particular note was an F1 tornado that

sprung out of a supercellular thunderstorm northwest of Colorado Springs in 1996 and was

captured by the newly installed NEXRAD WSR-88D Doppler radar (Bluestein 2000). This

tornado was also accompanied by accumulating hail, a category of the other major severe

weather hazard of eastern Colorado to be analyzed extensively in this study.

2. Severe hail

Like tornadoes, hailstorms are most prevalent across the mid-section of the U.S.,

with a maximum in the Great Plains region (Fig. 1.4a; Allen et al. 2015a). Large hail is often

associated with tornadoes due to the similar environmental and mesoscale ingredients

needed to produce hailstones of sizes capable of reaching the surface, including instability,

vertical wind shear, and storm-relative helicity (Das 1962, Thompson et al. 2003, Blair et al.

2017, Dennis and Kumjian 2017, Prein and Holland 2018). Hail is, by definition,

precipitation in the form of lumps of ice (AMS Glossary), which attain appreciable mass

from the accretion or riming of supercooled liquid water within a cloud. The necessary

ingredients required for hailstone formation and growth have been documented

extensively in the literature (Trapp et al. 2019, Allen et al. 2020b), and historical references

therein), although the complex microphysical aspects of hail and its growth within a storm

remain an ongoing research topic. Hailstones form via accretion of supercooled liquid

water onto a small particle known as an embryo. These embryos are typically graupel

particles in the High Plains, whereas frozen raindrops are common embryos in other

regions. Hailstones take a variety of trajectories through the upper parts of the cloud based

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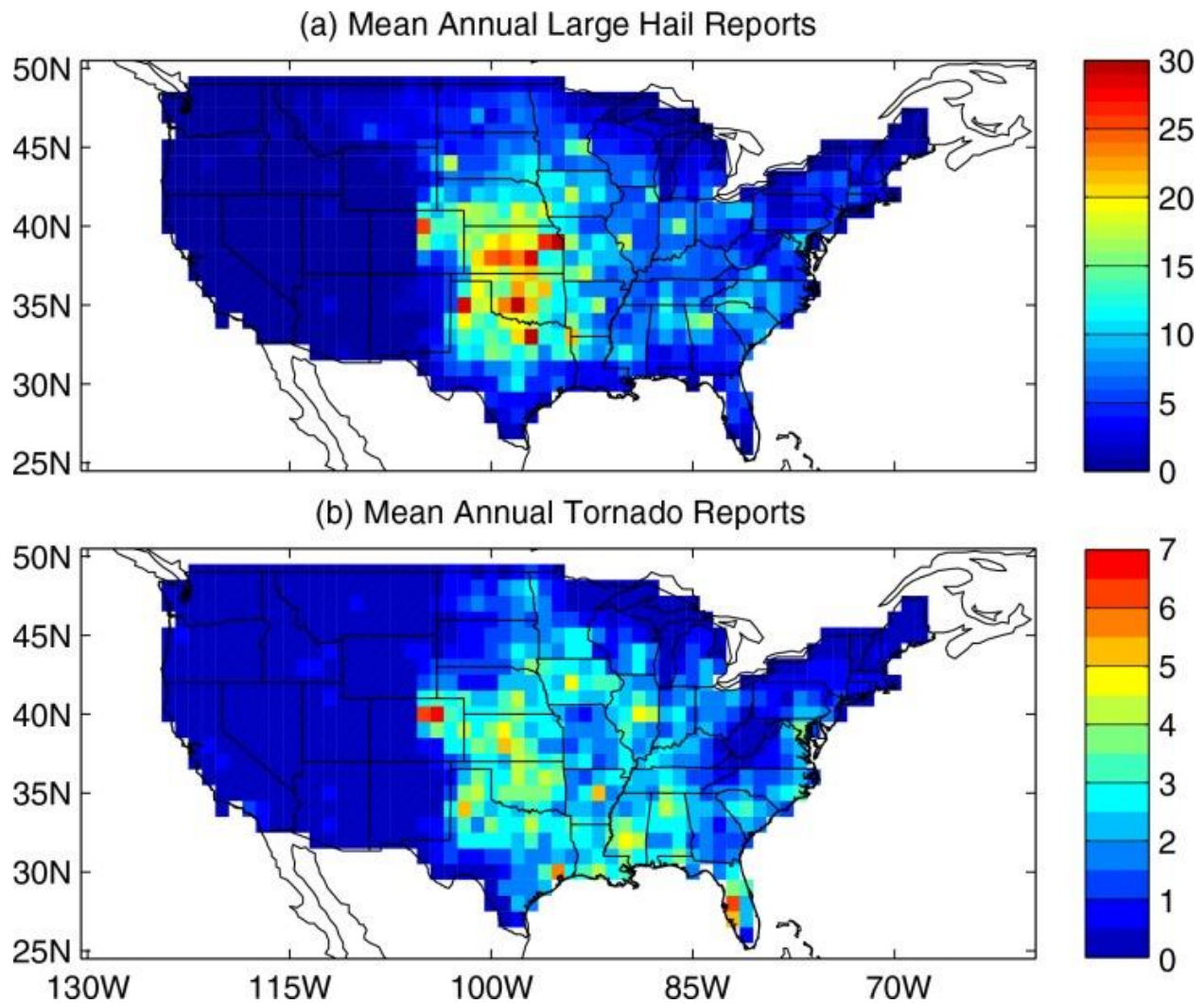
Fig. 1.4: (a) Annual mean number of severe hail reports > 25.4 mm, and (b) annual mean number of tornado reports, both plotted on a 1° X 1° grid. Adopted from Allen et al. (2015a), their Fig. 1.

on the complex interplay of horizontal and vertical air movements (Dennis and Kumjian 2017). During these changes in altitude, a hailstone may experience periods of dry growth in extremely cold regions, wherein its outer surface is ice, and wet growth in warmer regions, wherein its surface is opaque and coated in liquid (Lamb and Verlinde 2011). Often, a single hailstone can have multiple wet and dry layers. A complex balance of updraft strength, updraft volume, horizontal winds, and hailstone terminal velocity is

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necessary to lengthen the residence time of a hailstone within the cloud and thereby allow

for it to grow to a larger size. In general, updrafts which are too weak allow hail to fall out

at smaller sizes, whereas strong updrafts can keep hailstones lofted for a longer time,

allowing them to amass more supercooled water before gravity overcomes the updraft

strength and the hailstones fall out of the cloud. However, recent work by Kumjian and

Lombardo (2020) showed that a weaker yet wider updraft is seen at times of larger hail

sizes in model simulations. Further, their simulations reveal that weaker horizontal inflow,

lower meridional shear, and an expanding updraft in the region of hail growth all favor

longer residence times of the hailstone, thus allowing it to grow to larger sizes. In such

environments, the hailstone eventually becomes large enough to overcome gravity and fall

out of the cloud. More massive hailstones not only tend to be larger, but also have a faster

terminal velocity and higher kinetic energy, as diagnosed through power-law relationships

(Heymsfeld et al. 2014). Although most hailstones are modeled as spheres, they are often

quite rough with unique appendages due to the unique microphysical complexities of hail

growth processes within clouds. These complexities, particularly within strong or

supercell thunderstorms, remain to present challenges in accurate modeling of hail

formation and subsequent growth.

The SPC maintains a local hail storm report record from 1955. Hailstones in this

data record are considered to be severe if they have a size of at least 1.0 in (25.4 mm)[1], a

threshold that was adjusted upward from 0.75 in (19.1 mm) in 2010 after

recommendations from the media and emergency managers (NWS 2010). As with the

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[1] This dissertation will mostly use millimeters throughout when referring to hailstone sizes, unless English units aid clarity (such as in figures). The first time a particular size is mentioned, both inches and millimeters will be given, after which only millimeters will be used.

tornadoes, caution is advised when performing analysis with the severe hail data record

due to inhomogeneities and biases (Allen and Tippett 2015), and specific examples will be

given in the climatological discussion of Chapter 2. While U.S. hail reports are increasing

over time in large part due to population bias, the number of annual severe hail days, that

is, days in which at least one severe hailstone is reported in the U.S., has remained

relatively steady since the mid-1990s (Fig. 1.5; Allen and Tippett 2015). However, given
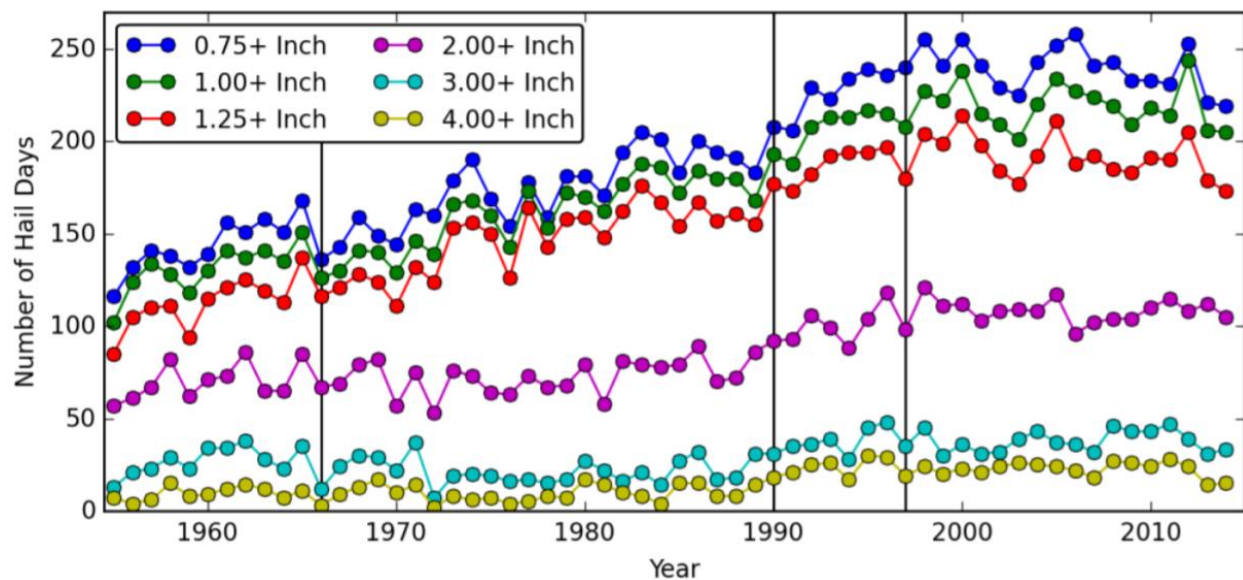
Fig. 1.5: Annual number of hail days (1955-2014) for various size thresholds. Vertical lines denote establishment of the National Severe Storms Forecast Center in 1966, and the approximate beginning and end of the WSR-88D Doppler radar installations in 1990 and 1997, respectively. Adopted from Allen and Tippett (2015), their Fig. 3c.

the measurement and data limitations, modeling and radar-based methods have been

developed to give an alternative approach to investigating hail climatology and its trends

over time. Such efforts include (but are not limited to) the radar-derived product

Maximum Estimated Size of Hail (MESH; Witt et al. 1998), the HAILCAST model which has

been used in conjunction with the Weather and Forecasting (WRF) model to estimate hail size in simulated convective storms (Adams-Selin and Ziegler 2016), and machine learning techniques (Gagne et al. 2017, 2019). Moreover, convective parameters have been combined and used to forecast environmental favorability of hailstorms. These have generally included parameters associated with supercell thunderstorms, such as CAPE, storm-relative helicity, and vertical wind shear, in addition to moisture availability (Brooks et al. 2003b, Allen et al. 2015a, Taszarek et al. 2019). Relationships have also been noted with hail occurrence and large-scale signals from Gulf of Mexico sea surface temperatures (Molina et al. 2016), ENSO (Allen et al. 2015b), and the Madden-Julian Oscillation (Barrett and Henley 2015).

Eastern Colorado is prone to large hail events (Doesken 1994, Changnon 1999, Cintineo et al. 2012, Allen and Tippett 2015, Allen et al. 2015a), and some particularly damaging events have occurred in recent years. The costliest hailstorm in Colorado state history, and one of the costliest in U.S. history, impacted the Denver metropolitan area on 8 May 2017, causing an estimated $2.3 billion in damage at the time of its occurrence (RMIIA 2018). Other destructive hailstorms impacted populated areas along the Front Range in 2018, including the 6 August 2018 event which resulted in the rare occurrence of at least a dozen human injuries and five animal deaths at the Cheyenne Mountain Zoo in Colorado Springs. In fact, 2018 broke multiple state records for the number and proportion of severe hail reports that were of the 50.8-mm+ and 76.2-mm+ varieties (Childs and Schumacher 2018), and Colorado bested Texas for the most hail losses in 2018 (State Farm 2019). The anomalous 2018 Colorado hail season will be the subject of Chapter 3. Then on 13 August 2019, the state record for largest hailstone was eclipsed when a 4.83-in (122.7-

mm) hailstone was measured in Kit Carson County. Arguably the most tragic hail event in

eastern Colorado that was not concurrent with a damaging tornado was a 30 July 1979

hailstorm in Fort Collins, which produced 4.5-in (114.3-mm) hailstones and resulted in 22

human injuries and one fatality (Fritsch and Rodgers 1981, Doesken 1994). Aside from

very large hailstones, the state of Colorado also sees its fair share of so-called "plowable"

hailstorms, that is, those in which a large amount of usually-small hailstones accumulate to

the point of requiring snow plows to remove them (Schlatter and Doesken 2010, Kalina et

al. 2016, Friedrich et al. 2019, Kumjian et al. 2019). Sometimes, a storm can produce both

very large hail and accumulating hail, such as the destructive 13 June 1984 hailstorm in

Denver, in which softball-size hail was reported in addition to a hail depth of 1 m in another

part of the city (Blanchard and Howard 1986). While hailstorms that impact populated

regions garner the most attention and media coverage, a large number of hailstorms impact

agricultural regions of eastern Colorado, posing an equally hazardous threat. In particular,

as will be highlighted in Chapter 5, small hail in large quantities or driven by a stiff wind

can be particularly damaging to fields of crops and lead to large crop loss and a

demoralizing state for farmers and ranchers.

3. Climate change influences

        While climate change impacts on tornado and hailstorm frequency will be the

subject of Chapter 4, it is of worth to give a brief overview of proposed projections from the

literature. From an ingredients perspective, strong convection requires the right

combination of instability, of which the most commonly used variable is CAPE, vertical

wind shear, a moisture source, and a trigger to initiate convection. CAPE and shear have

been generally seen to carry opposite trends in the future, with CAPE increasing and wind

shear decreasing as the climate warms (Trapp et al. 2007, Diffenbaugh et al. 2013, Robinson et al. 2013). However, Diffenbaugh et al. (2013) find more instances of high-CAPE-high-shear environments in a future climate, implying that the decreasing trend in shear is limited to days in which CAPE is also low. Indeed, recent pseudo-global warming (PGW) simulations show a tendency toward a more intense convective population, including thunderstorms capable of producing tornadoes and large hail, as measured by composite radar reflectivity, in the future across the CONUS (Rasmussen et al. 2017). Dynamical downscaling approaches have been utilized to project changes in the frequency of all hazardous convective weather (Gensini and Mote 2014, Gensini and Mote 2015, Hoogewind et al. 2017) and reveal increases in favorable hazardous convective weather environments in a future climate across most of the CONUS. For the individual hailstorm hazard, recent work has suggested that larger hail sizes will become more frequent relative to smaller hail in a future climate, owing at least in part to an elevated freezing level height, allowing smaller and slower-moving hailstones to melt more readily before reaching the surface (Brimelow et al. 2017, Trapp et al. 2019). This assertion applies specifically to the state of Colorado as well, as Mahoney et al. (2012) found a near disappearance of small hail reaching the surface in their high-resolution dynamically downscaled simulations. However, Trapp et al. (2019) caution that freezing height alone should not be used to draw conclusions regarding future trends in hailstone sizes, as other factors such as relative humidity must also be considered, and Tang et al. (2019) suggests a decrease in environments favorable to large hail over the Great Plains, including the eastern Colorado domain considered here. Less work has specifically projected tornado frequency in a future climate, although Trapp and Hoogewind (2016) performed pseudo-global warming

analysis of future tornadic thunderstorms and found that increased convective inhibition (CIN) contributed to some present-day tornadic storms not initiating in the future climate simulations despite enhanced positive buoyancy as measured by CAPE. In review, while environments favorable for hazardous convective weather are expected to increase in the future, changes in the frequency of realizing said environments, and pinpointing changes in individual hazards, are more uncertain and the subject of much ongoing research.

B. The Human Element

Although projecting frequency and intensity of severe convective hazards is shrouded in uncertainty, one thing that is certain is that as population grows and the built environment continues to expand, tornadoes and hailstorms present an increasingly concerning societal risk. Simply put, more people and property are becoming exposed to these hazards over time, and the risk of damage and loss is exacerbating. For example, a single large hail event can now easily amass more than $1 million worth of damage to property (Prein and Holland 2018), and in the years of 2018 and 2019, fifteen of the twenty-nine billion-dollar disasters in the U.S. were attributed to tornadoes and hailstorms, four of which impacted eastern Colorado (NCEI 2020). A similar relationship between damage and population exists with other hazards; for example, Klotzbach et al. (2018) showed that although trends in U.S. hurricane landfall frequency and intensity are relatively flat over the past century, increasing population along the Gulf and East Coasts has greatly exacerbated damage potential.

Human perceptions of weather and climate disasters and extreme weather events have generally moved from a belief that God sends such events as vengeance upon an

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immoral society, to one that acknowledges the role of religion yet explains extreme weather from natural scientific principles, and, more recently, to an assertion that humankind is exacerbating its own negative impacts by placing itself in vulnerable climatic regions or contributing to the factors which are driving climate change (Oberholzer 2011, Strader and Ashley 2016, Ashley 2020). In other words, while scientific advancements have helped meteorologists and climate scientists reconcile and explain the physical science of phenomena such as tornadoes and hailstorms, the fact that humankind continues to expand and place itself in areas prone to these hazards or in other vulnerable situations contributes to a growing susceptibility to negative impacts. It therefore behooves the meteorological researcher, especially in work which projects climate change impacts on the characteristics of weather hazards, to consider how human behaviors and patterns convolve into the threat and contribute to the overall scientific understanding. Out are the days of the meteorologist, economist, sociologist, phycologist, engineer, and geographer working on facets of weather and climate risk individually, and in are the days of interdisciplinary collaborations that aim to achieve a more complete understanding of the problem at hand through a synthesis of expertise across disciplines. The human is and always will be an integral part of the hazardous weather system, so incorporating their perceptions, risk factors, and adaptation and resiliency strategies into research contexts, is critical to advancement and ultimately saving lives.

Human elements of tornado risk have been researched rather extensively in recent years, and has served as a motivation to investigate societal impacts of other hazards. For example, Ashley et al. (2014) introduced the "expanding bull's-eye effect" for tornadoes, which describes how urban expansion and sprawl across U.S. cities is increasing the

number of people and things in the paths of tornadoes (Fig. 1.6). They describe how the

number of humans and housing units exposed to five simulated tornado tracks placed

across the Chicago metropolitan area increased by up to 49% between 1990 and 2010 due

to the expanding bulls-eye effect. Similar results apply to five other U.S. metropolitan areas
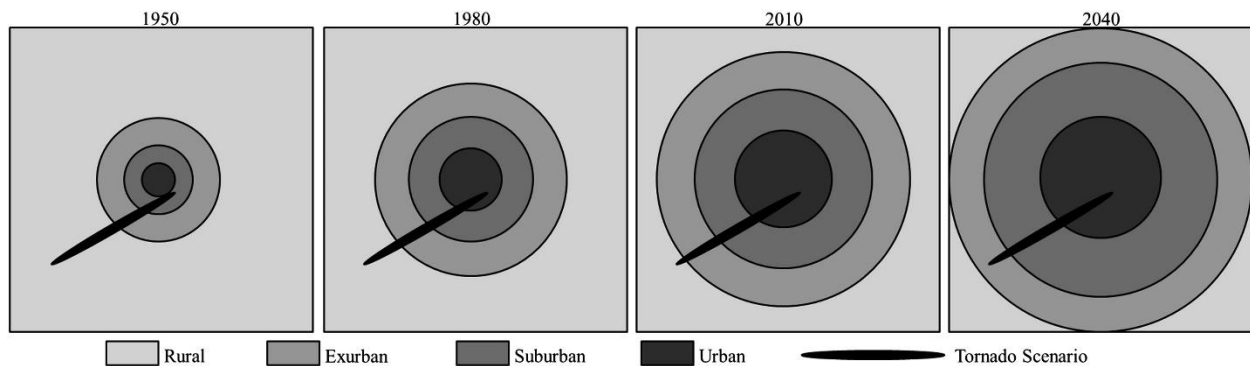
Fig. 1.6: Conceptual model of expanding bull's-eye effect, showing how a growing city increases human exposure to a tornado. From Ashley et al. (2014), their Fig. 4.

in a subsequent study (Rosencrants and Ashley 2015). Using Monte Carlo statistical

approaches, Strader et al. (2017) found a three-fold increase in tornado disaster potential

across the U.S. due to the combined factors of meteorology and population growth, with the

population effect outweighing the effect of doubling the number of tornadoes. Societal

impacts and financial losses due to hailstorms has also been on the rise in recent decades

due to an expansion of the built environment (Changnon 2009, Prein and Holland 2018,

Bouwer et al. 2019), without even considering changes in hailstorm frequency.

The growing and anticipated future rise in human exposure to tornadoes and

hailstorms does not necessarily imply that people perceive or believe this to be true for

them, and it says nothing about how they interact with the senders and content of threat messages for these hazards. Meteorologists and other decision-makers have a vital role in effectively informing the public before, during, and after a severe weather event. Recent efforts from the National Weather Service, such as Impact-based Decision Support Services (IDSS) and Impact-based Warnings (IBWs) have been formed with the idea that human impacts are just as important to communicate as are tornado intensity and hailstone size. Moreover, Integrated Warning Teams (IWTs) incorporate expertise from beyond the weather enterprise to conduct research and have conversations about developing more effective ways to communicate risk information to the public.

A major limitation to effective communication and mitigation of the negative impacts from tornadoes and hailstorms is the vulnerability of the population in question. As has become a major theme in disaster literature, vulnerable populations face a variety of socioeconomic barriers to receiving and responding to threats of convective weather hazards (Changnon et al. 2000, Pielke 2005, Bouwer 2011, Ashley et al. 2014, Strader et al. 2017, Childs and Schumacher 2018a). These include lack of technology, lack of education, language barriers, and diurnal occurrence of the hazard. While some of these challenges will be addressed in future chapters, of most application in this study is lack of sturdy or sufficient physical protection for people and their property or crops. Attention has been given to the insufficiency of mobile and manufactured homes to stand up against tornadoes, particularly in the Southeast (Liu et al. 2019, Strader et al. 2019) where this type of housing is prevalent. However, the role of effective risk communication is seen in its ability to deter people from purchasing these homes (Sutter and Poitras 2010). Physical property is also vulnerable to large hail, as seen in the numerous roof and car repairs

needed in the aftermath of a hailstorm. Of greater importance in the agricultural sector are

vulnerabilities of fields of crops, which, when destroyed by a hailstorm, can impose

significant financial losses and strains on the market (Shapiro et al. 1986, Battaglia et al.

2019, Bogen et al. 2020). This will be of particular interest in the interview protocol of

Chapter 5.

While not as pertinent to this study, it should be mentioned that other elements of

human dimensions in the severe weather story, particularly those regarding tornadoes,

have been investigated. Numerous studies exist that, for example, examine the tornado

warning process (Brotzge and Donner 2013), how humans respond to and comply to

warnings (Paul et al. 2015, Drost et al. 2016, Ripberger et al. 2019, Walters et al. 2020), the

relationships between decision-makers and their constituents (Schumacher et al. 2010,

Peppler et al. 2017, Childs and Schumacher 2018a), and the growing role of communicating

risk via social media platforms (Ripberger et al. 2014, Stokes and Senkbeil 2017). In

addition, risk communication and behavioral response research have emerged for other

weather hazards such as hurricanes (Demuth et al. 2012, Trumbo et al. 2014, Demuth et al.

2018) and flash floods (Morss et al. 2015, 2016).

In short, an overarching goal of this comprehensive study is to further elucidate the

need for interdisciplinary applications within physical, severe weather research.

Specifically, the assessment of future human exposure to tornadoes and hailstorms must

consider both meteorological effects due to climate change projections *and* human effects

of population growth and perceptions of vulnerability and warning messages. Rather than

generalize findings across a broad spatial area of the U.S., as has been done in most

previous work, an innovative aspect of this study is its focus on the localized domain of eastern Colorado, an area that lends itself well to a study of this sort.

C. Why Eastern Colorado?

The aforementioned motivation to couple severe weather projections with societal and behavioral implications is well-applied in a localized context to bear a greater merit to individual persons and the decision-makers who live in specific areas, as opposed to more regional analyses which have advanced the science but are generally less likely to appeal to individuals concerned with their specific residence. Arguments for studying the domain space of eastern Colorado have already been given but are worth summarizing. It should also be mentioned that the methods in this dissertation could easily be applied to other localized regions of the U.S., and in fact comparative studies are recommended as future work.

Eastern Colorado (Fig. 1.7) lies in the immediate lee of the Rocky Mountains, the largest mountain range in the U.S. and a major influencer of convective weather. It is here where warm, moist air from the Gulf of Mexico is advected northward and meets drier, cooler continental air. This interaction of air masses often creates instability within the atmosphere, which, when combined with other factors and realized, can result in thunderstorms during the warm season. In fact, many long-lived mesoscale convective systems or storm complexes initiate in this domain and then travel eastward across the nation's mid-section, providing half of the warm-season precipitation for regions such as the Great Plains (Geerts et al. 2015, Feng et al. 2019). Severe weather across this region, typically designated as the High Plains, typically occurs in environments of relatively low

Fig. 1.7: Location of eastern Colorado domain considered in this study (37-41°N, 102-105.3°W).

CAPE and speed shear but enhanced directional shear which is in part a consequence of the terrain. In this generally moisture-starved region, enhanced precipitable water and relative humidity are typically seen on severe weather days. Local topographical features also aid in convective weather across eastern Colorado, including the Palmer Divide south of Denver and the Cheyenne Ridge straddling the Colorado-Wyoming border. The Denver Cyclone, which forms within the Denver Convergence Vorticity Zone on many warm-season days, can serve as a trigger for rotating convection and is responsible for the high concentration of non-mesocyclonic tornadoes in the region. While tornadoes in this region tend to be weak, hailstorms can often be quite intense and produce both swaths of

accumulating hail and giant hailstones. Again, the complex terrain has influences on

hailstorm frequency and severity, not only due to the relatively shallow layer of above-

freezing air due to the high altitude, but also due to the intense convection that ensues

when an elevated mixed layer capping inversion is broken by strong positive buoyancy.

The relatively dry air in the lowest levels of the atmosphere across eastern Colorado also

contributes to occurrence of larger hailstones reaching the surface, as the dry air inhibits

melting (Mahoney et al. 2012, Trapp et al. 2019). These topographical intricacies create a

severe weather environment very different from that of the Great Plains, Midwest, and

Southeast U.S., and yet eastern Colorado is a relative maximum in both tornado and severe

hail occurrence. Moreover, models often struggle with representing hail and other weather

phenomena across eastern Colorado due to the topography and underestimation of

moisture (e.g., Gensini et al. 2014, Allen et al. 2015a). Therefore, a detailed analysis of

severe weather in this area of eastern Colorado can reveal unique climatological features

and serve as a framework for comparison analyses of other severe weather environments.

Beyond the meteorological appeal of eastern Colorado is the unique population

dichotomy that directly impacts current and future human exposure and risk from

convective weather hazards. The Front Range urban corridor, stretching roughly from

Pueblo in the south to Fort Collins in the north (Fig. 1.1), is a narrow, rapidly growing area

with major technological and industrial enterprises. The capital city of Denver alone has

grown by more than 100,000 people since 2011 (The Denver Post 2018b), and several

other Front Range counties are projected to grow by more than 50,000 people by the year

2040 (Colorado State Demography Office, 2012). Conversely, the eastern part of the

domain is largely agrarian land with very few sizeable towns, and population here is

expected to generally remain flat or decrease in the coming decades, according to projections prepared by the State Demography Office (2012). Moreover, in an Associated Press review of Economic Innovation Group data, Colorado was found to have one of the largest economic gaps between urban and rural populations of any U.S. state (The Denver Post 2017). Yet the agricultural production in these areas, which is primarily dryland wheat and corn crops, contributes approximately $41 billion to the Colorado state economy each year (CSU 2012). The stark population divide set up between these two areas of eastern Colorado presents a unique landscape across which to study impacts from severe weather hazards, as the implications are very different for the different populations. For example, the urban Front Range corridor is susceptible to physical damage to homes and vehicles from the occasional tornado and the more frequent hailstorms, as has been evidenced by several damaging events in recent years. Traffic can also be disrupted in this area due to accumulating hailstorms. On the other hand, the sparsely populated eastern Plains is largely impacted by tornadoes and hailstorms through crop losses, which can accrue major financial losses for agriculturalists and consequently put strains on local markets.

The complex interplay between weather hazards and socioeconomic factors across eastern Colorado has been affirmed by indices that measure the vulnerability of populations. The Social Vulnerability Index (SOVI; Cutter and Emrich 2017) incorporates over twenty socioeconomic variables in its formulation related to age, ethnicity, workforce, housing units, and wealth. In the years 2010-2014, almost all Front Range counties are designated as a 'Low' SOVI, and many eastern Plains counties have a 'High' SOVI (Cutter and Emrich 2017). In other words, the urban areas of eastern Colorado appear, at least by

this metric, to have a high resiliency and ability to cope with the effects of natural hazards, whereas the rural areas further east are hindered in their adaptation by a variety of socioeconomic factors, which can influence how this population receives and perceives threats of severe weather. The results presented in the following chapters thus have major implications on both current and future decisions made by meteorologists, urban planners, insurance agents, and others across this topographically and demographically diverse landscape.

D. Research Outline

The analysis begins in Chapter 2 with updating the climatology of tornadoes and severe hail across the eastern Colorado domain. Several unique temporal and spatial trends of these hazards will be discussed, and recent damaging events will be highlighted. The year 2018 broke several state records for hailstorm characteristics, which warrants its special emphasis in Chapter 3. Having established a climatological framework, Chapter 4 aims to answer the overarching research question of a changing human exposure to tornadoes and hailstorms by the end of the 21st century. Future projections of these hazards are presented by comparing synthetic reports between future and control simulations of high-resolution dynamically-downscaled climate model output. Population effects are also given consideration, specifically through use of the Shared Socioeconomic Pathways of future growth scenarios. Monte Carlo statistical models are used to simulate tornado and hail events and the resulting human exposure across numerous combinations of meteorological and population projections, culminating in a range of potential changes in human exposure. Even in scenarios where human exposure decreases, agricultural land exposure could be enhanced. This motivates the interview study detailed in Chapter 5,

wherein eastern Colorado farmers and ranchers are interviewed to better understand their

perceived vulnerabilities and responses to warnings, specifically for hailstorms. Chapter 6

concludes the dissertation with a synthesis of key take-away messages and

recommendations for future work. Overall, the practical applications and implications for

future risk detailed herein present important opportunities for furthering understanding of

the changing severe weather landscapes, both in eastern Colorado and in other localized

regions of the U.S., and ultimately promoting the protection of life and property.

CHAPTER 2: AN UPDATED SEVERE HAIL AND TORNADO CLIMATOLOGY FOR EASTERN

COLORADO[2]

To set the stage for projecting future risk and human exposure to severe hail storms and tornadoes across eastern Colorado, it is of worth to provide an updated climatology of these hazards to serve as a baseline. This chapter begins by briefly rehearsing the current state of knowledge about Great Plains severe weather environments and affirms eastern Colorado as a hot spot for both severe hail storms and tornadoes. After discussing the various biases in the severe weather datasets that must be taken into account, temporal and spatial trend analyses are presented for various statistics. Interesting features emerge in both the severe hail and tornado time series, and opposite behaviors in their temporal trends are revealed. While the majority of the analysis ends with the year 2017, the year 2018 saw a particularly damaging and record-breaking hail season across eastern Colorado. Thus, a sidebar discussion of this season and the potential meteorological and societal influences is also included in this chapter (Childs 2018, Childs and Schumacher 2018). Finally, a summary of key take-aways from the climatological analysis is given, which serves as motivation to investigate how or if the trends presented here will continue in the future.

A. Historical Overview

Establishing a climatological framework is a helpful way to begin any severe weather research endeavor, as it provides a base on which to perform analysis and also

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[2] Adapted from Childs and Schumacher (2019, *JAMC*)

gives a glimpse as to past and present characteristics of the hazard. Climatological studies

which analyze frequency, strength, variability, and spatial patterns of tornadoes in a broad

sense have existed for many decades (e.g,. Kelly et al. 1978, Doswell and Burgess 1988,

Brooks et al. 2003b, Verbout et al. 2006, Farney and Dixon 2015, Agee et al. 2016, Gensini

and Brooks 2018). In addition, filtered climatologies have been established for subsets of

tornadoes and their attributes, such as violent tornadoes (Concannon et al. 2000),

nocturnal tornadoes (Kis and Straka 2010), cold-season tornadoes (Childs et al. 2018),

tornado intensity assessments (Strader et al. 2015), and tornado deaths (Ashley 2007, Agee

and Taylor 2019). The influence of teleconnections on the variability of the tornado record

has also been analyzed (Gensini and Marinaro 2016, Lee et al. 2016, Cook et al. 2017, Allen

et al. 2018, Molina et al. 2018, Tippett 2018). Additionally, severe hail and wind

climatological studies have become more frequent in recent years (e.g., Cintineo et al. 2012,

Allen and Tippett 2014, Gensini and Allen 2018, Edwards et al. 2018).

The aforementioned climatological studies of severe weather, most of which cover a

broad region of the U.S., are advantageous for establishing long-term trends and providing

a general idea of where and how severe weather hazards are distributed. Often lacking,

however, are the impacts of small-scale features that can lead to unique climatological

patterns over a much smaller area. Moreover, non-meteorological biases inherent in the

data records can be exposed more fully on smaller scales and must be acknowledged in

analyses. Localized climatologies can also appeal to local residents in ways that national-

level analyses cannot by specifically focusing on severe weather patterns where someone

lives (e.g., Guo et al. 2016). The eastern Colorado domain considered here features both

intricate topographical influences on convection and a stark population distribution, as

discussed in Chapter 1, yielding small-scale climatological intricacies. While there have

been several case study analyses of Colorado severe weather events, few attempts have

been made at developing robust climatologies for tornadoes and severe hail. The Colorado

Climate Center houses general statistics about tornadoes, including an analysis by Spears

(2017) that presents state and county level statistics of Colorado tornadoes, partitioned by

intensity, for the period 1950–2012. However, the study does not account for biases in the

data record nor explore potential reasons for some of the trends seen. Former Colorado

State Climatologist Nolan Doesken presented a unique cultural history of hail storms in

Colorado as well as general climatological statistics in his 1994 overview (Doesken 1994),

but since then no comprehensive hail climatology has been published. The tornado and

severe hail climatologies and associated statistics herein thus encapsulate a comprehensive

analysis of these hazards for an eastern Colorado domain and serves as a foundation for the

forthcoming chapters that will explore projected changes in the tornado and severe hail

landscape due to climate change and population growth.

B. Data and Methods

Any climatological study that makes use of the U.S. severe weather data records

must acknowledge numerous deficiencies in the existing data and make carefully

considered choices when determining the extent of data used. Despite the limitations, the

SPC maintains the largest and most complete severe weather database in the world

(Schaefer and Edwards 1999). Severe weather data are available in tabular format, which

give numeric values of, for example, tornado intensity rating, path length and width, and

hail size, as well as geographical coordinates of the event location, loss amounts, and

casualty statistics. In addition, each severe weather hazard comes in a shapefile for use in a

Graphical Information System (GIS) framework. The tabular files and a link to the

shapefiles are publicly available at https://www.spc.noaa.gov/wcm/. This study makes

use of the tornado and severe hail data sets, both of which contain noteworthy biases and

inhomogeneities.

1. Tornado data record

The SPC tornado database currently contains tornado events from 1950 to present.

Over such a long period, many different changes to reporting methodology, rating systems,

and definition changes have led to biases in the data record. While a thorough treatment of

the issues has been given in previous work (Doswell and Burgess 1988, Schaefer and

Edwards 1999, Verbout et al. 2006, Agee and Childs 2014), an overview of the key biases

present is worthwhile for establishing the eastern Colorado tornado climatology.

While the middle of the 20th century saw a building interest in severe weather and

tornado forecasting, with numerous field campaigns and programs, it was not until the

early 1950s and the establishment of the Severe Local Storms unit (SELS) that procedures

for reporting, documenting, and assigning intensity ratings to tornadoes began to be

standardized (Doswell 2007). As a result, almost all modern tornado analyses begin with

either the year 1953 or 1954, and this study will also start with 1953. The next major

milestone in tornado documentation came in 1974 with the introduction of the Fujita (F)

Scale for rating tornadoes. The F-scale was applied to tornadoes that occurred before

1974, but again relied primarily upon newspaper reports and photographs. Not

surprisingly, pre-1974 tornadoes were sometimes given incorrect F-scale ratings (Grazulis

1993), and Agee and Childs (2014) exposed enhanced F2 counts at the expense of F1

counts in the period 1953–1974, which does not stem from meteorological factors. A more

prominent feature in the tornado data related to F-scale ratings is due to the advent of

NEXRAD WSR-88D Doppler radar network, which was periodically installed in Weather

Forecast Offices across the country during the 1990s (Crum et al. 1998). The WSR-88Ds

allowed meteorologists to more easily identify tornado vortex signatures on radar, which

in turn led to greater observation of tornadoes, especially weak ones, by people on the

ground (Bieringer and Ray 1996). Time series plots of F0 tornado reports show a huge

jump in the mid-1990s, explainable only by the advent of Doppler radar (Verbout et al.

2006, Agee and Childs 2014). It therefore behooves the researcher to use caution when

performing analysis with F0 tornadoes prior to the late-1990s. Crum et al. (1998) reported

that the last WSR-88D was installed in 1997, and all with coverage in the eastern Colorado

domain were installed by early 1996; therefore, a start year of 1997 has been selected for

this study. Yet another change was instituted in 2007, as the Fujita Scale was upgraded to

the Enhanced Fujita (EF) Scale, which introduced a tornado damage rating scale based on

numerous damage indicators (DI) and degrees of damage (DoD; McDonald and Mehta

2004). The switch to the EF-scale has produced some subtle changes in national tornado

trends but more significantly has revolutionized tornado storm surveys and damage

analysis (Edwards and Brooks 2010, Edwards et al. 2013). Further amendments to the EF-

scale are forthcoming, including modification of DIs and a greater emphasis on wind speed

as a rating metric (LaDue et al. 2018). Finally, an increasing trend exists in all (i.e. (E)F0-

(E)F5) tornado reports across CONUS simply due to increases in population (Potvin et al.

2019) as well as public interest and technological advancements. However, when (E)F0

tornadoes are excluded from analysis, there is in fact no appreciable trend in (E)F1+

tornadoes, at least on the national level (Verbout et al. 2006, Gensini and Brooks 2018).

Due to the high fraction of (E)F0 tornadoes in the Colorado record, they are included in the

analysis presented herein; however, the time frame of the climatology is restricted to

1997–2017 to provide a more accurate representation of trends.

2. Severe hail data record

      The current SPC hail data record extends from 1955 to present day, nearly as long

as the tornado record. In perhaps the most thorough synthesis of the characteristics of

severe hail data, Allen and Tippett (2015) note that advancements in technology,

procedures, and awareness have led to a non-meteorological increase in severe hail reports

over the years. Particularly in the 1980s and 1990s, the formation of the SPC, growth of the

storm spotter network, and advent of Doppler radar led to increased hail reporting. In

addition, the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS; Reges et

al. 2016) was formed in the late-1990s, which has since become an additional source of hail

reporting through public outreach. Additional efforts such as the Severe Hazards Analysis

and Verification Experiment (SHAVE; Ortega et al. 2009) and Colorado Hail Accumulation

from Thunderstorms (CHAT; Freidrich et al. 2019) projects have also increased interest in

and reporting of hail, and recent crowdsourcing success in Switzerland hail reporting may

be a path forward to improved precision (Barras et al. 2019). Given this increasing

interest, population growth, and technological advancements, severe hail data prior to the

late-1990s is suspect and likely suffers from many more missing reports compared to the

more recent decades. As such, this study will follow Allen and Tippett (2015) by focusing

on severe hail reports since 1997. A change in the threshold of severe hail was made in

2010, with an upward shift from 19.1- to 25.4-mm hail diameter (NCEI 2009). This minor

change has led to a nontrivial decrease in 19.1-mm hail reports since 2010 (Allen and

Tippett 2015), and thus the Colorado severe hail climatology presented here will consider

only those hail reports which meet the current severe threshold of 25.4 mm.

There is also an overwhelming tendency for hailstone sizes to be reported based on

the sizes of reference objects used by the NWS in forecasts and severe thunderstorm

warning texts (Sammler 1993, Doswell et al. 2005, Allen et al. 2017). For example,

hailstone size reports are clustered around 25.4 mm (quarter-sized), 1.75 in (44.5 mm,

golf-ball-sized), and 2.75 in (69.9 mm, baseball-sized). There is no reason to believe that

hailstones preferentially hit the surface at these sizes, but the data record reveals very few

reports of other equally-likely sizes such as 1.1 in (27.9 mm) or 2.25 in (57.2 mm). Blair et

al. (2017) found that hail sizes recorded in the SPC database are actually underestimates of

actual hail size. This can be due to the shattering of hail upon impact, melting that occurs

between impact and measurement, and the tendency for the largest hail stones in a storm

fall in a narrow swath (Changnon 1997, Blair et al. 2017). Further, while instructions for

measuring hailstone size are available to trained spotters and the public, there is still

human subjectivity and error in taking hail measurements.

Arguably the greatest issue with the severe hail database is population bias, namely

the clustering of severe hail reports near population centers and roadways, as shown by

Allen and Tippett (2015). Population bias was a particular concern in the early decades of

severe hail reporting given the lack of standardized reporting procedures and the absence

of Doppler radar (Davis and LaDue 2004). However, even today severe hail is more likely

to be reported where people are around to measure them and underreported in more rural

areas. This is in contrast to tornadoes in rural areas: although given a weak intensity rating due to lack of appreciable damage, tornadoes are easier to see and can be confirmed with storm surveys, but confirming that hailstones actually fell and of what size in rural areas is very difficult. For example, in the Hail Spatial and Temporal Observing Network Effort (HailSTONE) wherein seventy-three storms were targeted for high-resolution hail surface measurements throughout 2011-2015, an average of sixty-six hailstone measurements were made per storm, compared to an average of three in the corresponding storms within the SPC *Storm Data* records (Blair et al. 2017).   Population bias has a rather unique influence on the eastern Colorado hail distribution (as will be shown in Section 4), which has a stark population contrast between the urban Front Range corridor and the rural eastern Plains. It is also important to note that in addition to severe hail being reported more readily in populated areas, property risk from severe hail is also enhanced in areas where people live, a topic to be explored in future work.

3. Summary and domain

According to the SPC severe weather data archives, 2050 tornadoes were reported in the state of Colorado between 1953 and 2017, for an average of 31 per year. Approximately 96% of these tornadoes occurred in the eastern half of the state, which motivates a western border of the domain to be set at 105.3°W longitude, roughly coinciding with the eastern edge of the Foothills (Fig. 1.7). This is not to diminish significance or societal impacts of tornado and hail events that occur in mountainous terrain and western Colorado, but these events are too anomalous, are likely underreported, and affect far fewer people to justify inclusion in this study. The eastern half of Colorado, however, presents two very different societal regimes, with the developed

business and technology hubs along the urban corridor abutting the foothills and the traditional agriculture and ranching communities further east. Moreover, the selected domain lies in the lee of the Rocky Mountains, which have unique synoptic and mesoscale effects on severe weather. The tornado climatology presented in Section C will investigate all (E)F-scale intensity categories, and in Section D, "severe hail" will refer to hailstones documented as at least 25.4 mm in diameter.

C. Eastern Colorado Tornado Climatology

Over the full record (1953–2017), an increasing trend is noted for both (E)F0 and (E)F0+ tornado count time series (Fig. 2.1a), and these two time series are nearly identical in the more recent period when (E)F0 counts are more reliable (Fig. 2.1b). Statistical significance of both tornado and severe hail trends in the following two sections is measured in two ways: first, a Student's t-test determines if the slope of the linear regression line is statistically different from zero, and second, a Mann-Kendall non-parametric test (Mann 1945, Kendall 1975) assesses whether a monotonic trend exists in the variable of interest over time. The Mann-Kendall test is especially useful in confirming linear trend analysis for time series with outliers or large variability. As expected, most tornadoes across eastern Colorado of the (E)F0 variety that are weak and often non-mesocyclonic. In Colorado, (E)F0 tornadoes account for 85% of total tornadoes in the more recent period (Table 2.1). In fact, 96% of tornadoes in the more recent period across eastern Colorado were of either (E)F0 or (E)F1 intensity, with only 3% of tornadoes rated as "significant" (i.e., (E)F2+). Even when considering tornado data back to 1953, only 6% of eastern Colorado tornadoes have been significant, and only one tornado in the modern record has been rated above an (E)F3 (an F4 in Baca County on 18 May 1977 that actually
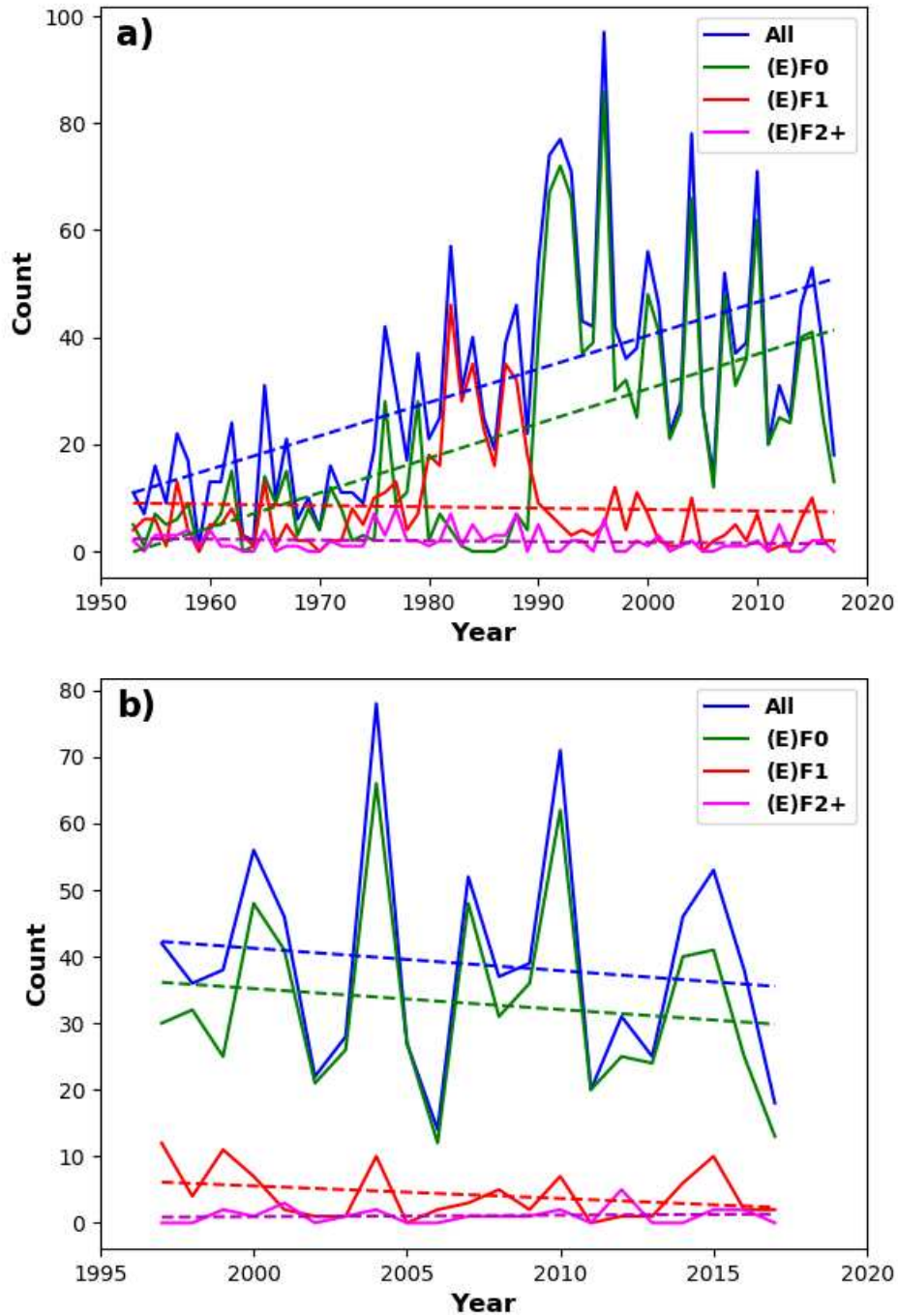
Fig. 2.1: Trends in eastern Colorado tornado counts for (a) 1953-2017 and (b) 1997-2017, partitioned by (E)F-scale intensity.

began its track in Oklahoma). This is not to say that the domain has been spared tornado

destruction, but most of the tornadoes across the eastern Plains are weak and/or are given

low ratings due to the lack of structures to damage. Tornadoes impacting major

metropolitan areas along the Front Range are a rare occurrence, although an EF3 tornado

that tore a path through more populated areas between the cities of Greeley and Fort

Collins resulted in dozens of injuries and one fatality in the town of Windsor (NWS Boulder

2008). Aside from the Windsor tornado of 2008, the other five (E)F3 tornadoes in the

Table 2.1: Eastern Colorado tornadoes partitioned by (E)F-scale rating

	1953-2017	**Percent**	**1997-2017**	**Percent**
(E)F0	1342	67%	693	85%
(E)F1	533	27%	89	11%
(E)F2	103	5%	17	2%
(E)F3	21	1%	6	1%
(E)F4	0	0%	0	0%
(E)F5	0	0%	0	0%
UNK	12	1%	12	1%
Total	***2011***		***817***	

domain since 1997 occurred in 1999, 2000, 2001, 2007, and 2015. The most catastrophic

of these (E)F3 tornadoes was the 28 March 2007 tornado that produced major damage in

the town of Holly in Prowers County, killing two people and injuring several others (The

Denver Post 2007). The only other killer tornado in the modern data record occurred in

1960 near Holyoke, Colorado. This tornado, which killed two people, was also posteriorly

given an EF3 rating. Since 1950, no tornado rated weaker than (E)F3 has resulted in

fatalities, which is consistent with national statistics showing almost all killer tornadoes

being rated (E)F2 or greater (Ashley 2007). However, prior to 1950, when warning

methods were much more rudimentary or nonexistent, Grazulis (1993) reports eleven

killer tornadoes in Colorado, most of which occurred in rural areas. The highest fatality

count from a single tornado was recorded on 10 August 1924 near the town of Thurman,

when nine children and one woman died when a tornado ripped through their farmhouse.

The next thing to note about eastern Colorado tornadoes is the behavior of the (E)F0

and (E)F1 time series in the 1980s. This entire decade shows an absence of (E)F0 tornado

reports, with very few or zero (E)F0 tornadoes reported each year. This is coupled by an

associated spike in (E)F1 tornadoes. At the dawn of the 1990s, (E)F0 tornado counts

suddenly jump upward to levels not seen in the prior decades, while (E)F1 tornado counts

fall back to a level consistent with the 1970s. The major uptick in (E)F0 tornadoes in the

1990s can be explained in part by the advent of Doppler radar, but there is no reason to

believe why (E)F0 tornadoes should disappear entirely from the data record for several

years in the 1980s. From a meteorological perspective, there were at least three tornado

outbreaks during this decade: a 3 June 1981 outbreak that produced seven (E)F1+

tornadoes, including two (E)F2 tornadoes in the Denver metropolitan area that caused (at

that time) $15 million in damage (Szoke et al. 1984); a 15 June 1988 outbreak that included

a damaging (E)F3 tornado in southern Denver (Szoke et al. 2006); and eleven tornadoes

over the course of 7-9 July 1988, of which nine were given an (E)F1 rating. These outbreaks

may help explain the jump in (E)F1 tornado counts, but even in tornado outbreaks one

would expect at least some tornadoes to be assigned an (E)F0 rating. The population of the

Front Range urban corridor increased in the 1980s as well, but expansion had been

ongoing before this time. Field campaigns, including JAWS in 1982 and CINDE in 1987, and

at least two NOAA exercises in which "forecasters issu[ed] warnings and chase crews tried

to verify" (E. Szoke, personal communication), occurred in the 1980s, yet do not explain

why (E)F1 tornadoes would be necessarily favored over (E)F0 tornadoes. Reporting

standards and local office overreporting are other potential influences, but in any case, the

(E)F0 counts rebounded and increased substantially in the 1990s.

A closer look at Fig. 2.1b reveals that for the more recent period of 1997–2017,

there is a slight decreasing trend in all tornado reports, influenced by the concurrent slight

decrease in (E)F0 tornado reports. There is little to no appreciable trend for the (E)F1 and

(E)F2+ records over this time (slopes of linear fit line = -0.19 and 0.02, respectively), which

is consistent with recent research on a national level (Verbout et al. 2006, Brooks et al.

2014, Coleman and Dixon 2014, Clark 2017). However, while overall changes in U.S.

tornado counts are small, there have been reported changes in the annual count variability

(Brooks et al. 2014), annual count volatility (Tippett 2014), and efficiency of tornado days,

that is, how many tornadoes occur on a day in which at least one tornado occurs (Elsner et

al. 2015). For the local eastern Colorado domain, Fig. 2.2 shows the number of tornado

days over the two periods of interest. The resulting linear trends are very similar to those

of tornado counts, with statistically significant increasing trends in (E)F0 and (E)F0+

tornado days when the entire record is considered, but slight decreasing trends in all but

(E)F2+ tornado days in the more recent period. This further validates that reports of

tornadoes across eastern Colorado since 1997 have not become more numerous despite

the increasing population. Gensini and Brooks (2018) showed similar results of decreasing

tornado frequency across the Great Plains region specifically since 1979 using the

Significant Tornado Parameter from North American Regional Reanalysis (NARR; Mesinger

et al. 2006) data.
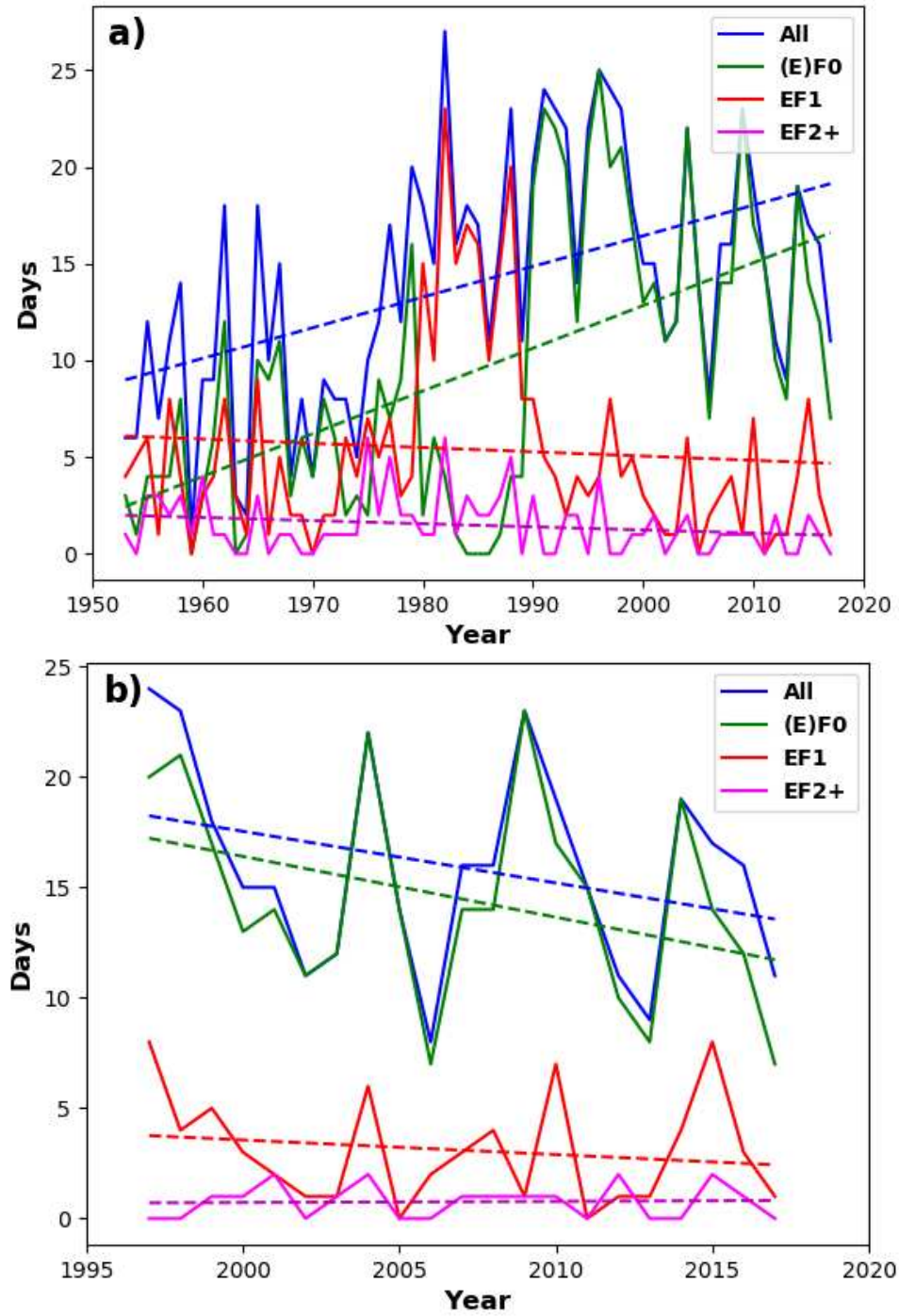
Fig. 2.2: As in Fig. 2.1, except for tornado days i.e. the number of days per year in which at least one tornado of given intensity was reported.

Tippett (2014) defines volatility of an annual report time series as the standard deviation D_i of a differenced count, where D_i is the difference in the number of reports in year i and the number of reports in year i-1, that is $D_i = N_i - N_{i-1}$. This method transforms a supposed nonstationary data set into one which has stationary statistics, and thus the volatility "measures the expected range of the change in reports from one year to the next (Tippett 2014)." Tippett (2014) found that the volatility in the F0+ and F1+ tornado count time series both more than doubled from the period 1980–2004 to 2005–2013, with values in the more recent period of 439.7 for F0+ and 268.8 for F1+ respectively. This method is employed for both tornadoes and severe hail in the Colorado domain for two recent decades (1998–2007 and 2008–2017), with results presented in Table 2.2. In contrast to the national-level findings of Tippett (2014), the Colorado tornado count time series show a slight decrease in volatility in the 2008–2017 decade across all (E)F-scale intensity bins. The magnitude of the volatility is much lower in Colorado than for the entire U.S. due to the smaller sample size and use of more recent time periods; therefore, it is more useful to examine the relative changes in volatility between these two decades rather than focus on actual values. For example, Tippett (2014) notes reporting practices in earlier years can influence volatility, but changes in the 2000s seem to be linked to changes in the environment, which may be hard to capture on such a local scale. Colorado tornado days show only a slight increase in volatility in the more recent period. The difference between the means of the two decadal time series of differenced counts D_i were tested for statistical significance using the non-parametric Wilcoxon signed-rank test (Wilcoxon 1945) and showed no significant difference. In other words, the variability of tornado counts and days across eastern Colorado over the two most recent decades is quite small throughout

Table 2.2: Tornado and hail volatility, computed by taking the standard deviation of the differenced tornado and hail count time series, for two recent decades.

	VOLATILITY OF TORNADO COUNTS		VOLATILITY OF TORNADO DAYS	
Intensity	**1998-2007**	**2008-2017**	**1998-2007**	**2008-2017**
(E)F0+ (All)	27.89	22.38	5.56	4.78
(E)F0	5.77	4.39	5.50	5.66
(E)F1	23.80	18.21	2.94	3.87
(E)F2+ (Sig.)	1.58	2.51	1.14	1.22

	VOLATILITY OF SEVERE HAIL COUNTS		VOLATILITY OF SEVERE HAIL DAYS	
Size	**1998-2007**	**2008-2017**	**1998-2007**	**2008-2017**
1.0"+	85.39	127.98	12.92	13.81
2.0"+	14.57	25.35	4.53	5.43
3.0"+	3.74	2.97	2.32	2.20

all size bins, in contrast to what Brooks et al. (2014) found over a much larger domain. Testing the sensitivity of the two selected periods did not yield any appreciable difference in volatility.

Tornadoes have occurred throughout most of the eastern Colorado domain (Fig. 2.3), but a preference is clearly seen abutting the Foothills along the north-central urban corridor. Many tornado reports are also scattered throughout the eastern Plains, which has much less population. To assess the level of population bias in the tornado data, Fig. 2.4 presents plots of starting lat-lon points for all tornadoes across the domain since 1953 (Fig. 2.4a), as well as a smoothed version (Fig. 2.4b) in which the tornado data has been upscaled to a larger grid with cells of 0.25° latitude by 0.275° longitude. This upscaling process is often done with SPC tornado data to account for erroneous reporting of starting
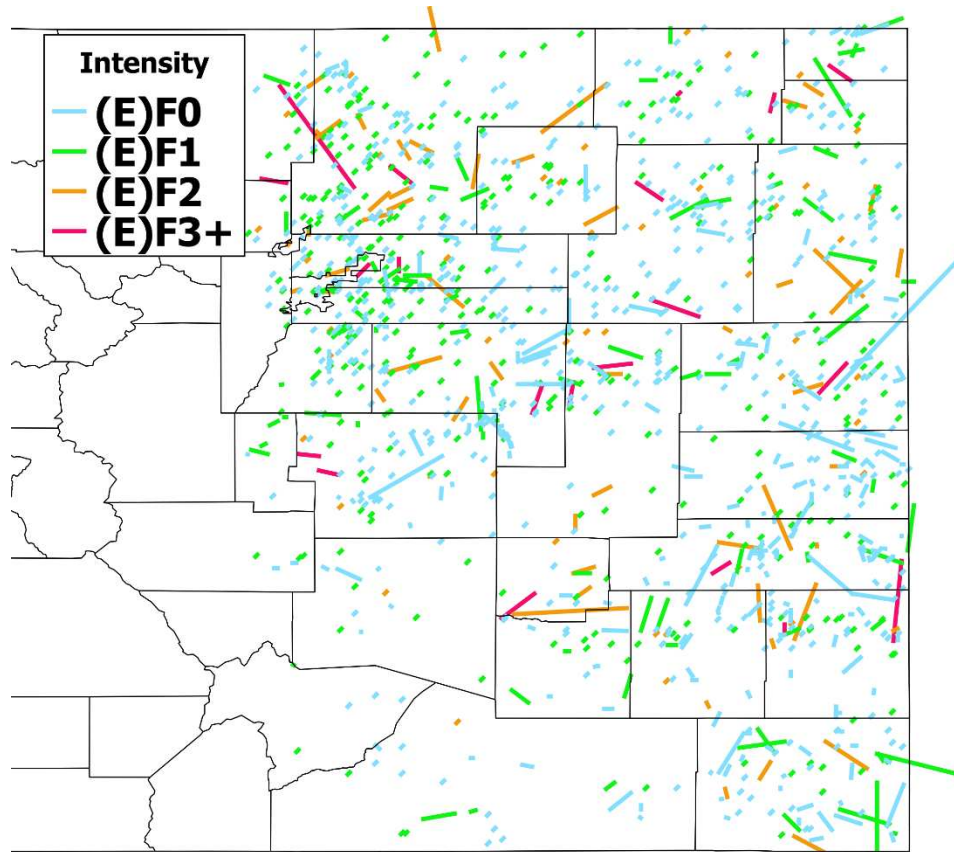
Fig. 2.3: All tornado tracks for the eastern Colorado domain for the period 1953–2017, partitioned by (E)F-scale intensity rating. Data is taken from https://www.spc.noaa.gov/svrgis/.

lat-lon locations of tornado tracks (e.g., Brooks et al. 2003, Hoogewind et al. 2017). Finally, to account for the inhomogeneities in the data record described in Section 2, similar plots of points and smoothed grids of tornadoes for the more recent period of 1997–2017 are presented in Figs. 2.4c-d. The same general pattern is noted among both periods, with a maximum in tornado reports near Denver International Airport (DIA). The northern half of the domain is climatologically more tornadic compared to the southern half, aside from a relative maximum near the town of Lamar at the intersection of Prowers, Bent, and Kiowa counties in southeastern Colorado. A local bull's-eye of reports is also found just north of
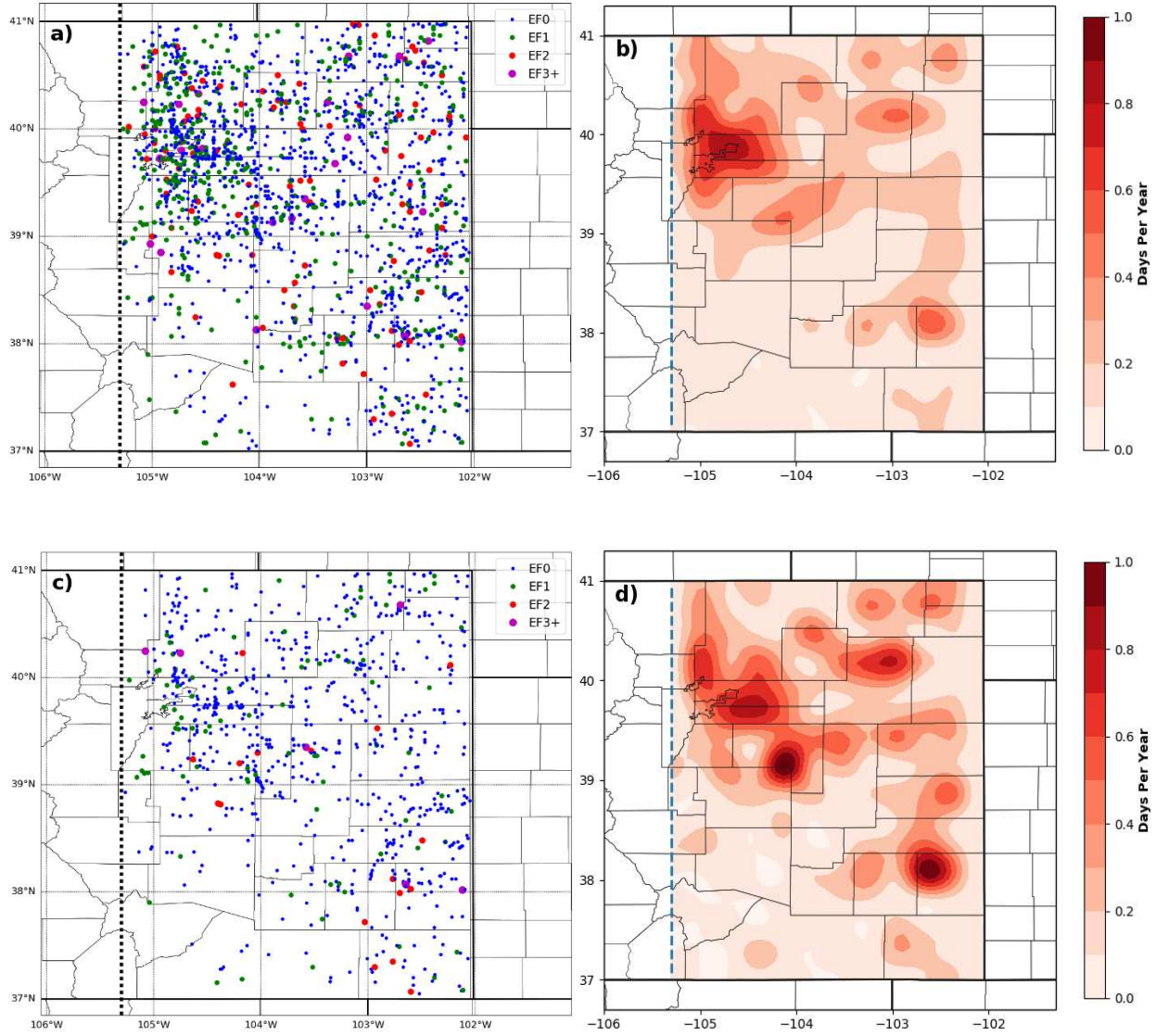
Fig. 2.4: Starting lat-lon tornado points (a,c) and gridded annual tornado reports (b,d) for the periods 1953–2017 (a,b) and 1997–2017 (c,d). The gridded reports are smoothed from a 0.25° latitude X 0.275° longitude grid.

the Palmer Divide in southwestern Elbert County, which likely corresponds to the many

weak tornadoes that form along the DCVZ. The domain space south and west of Pueblo,

where relatively few people live, sees the least tornado reports. Given the relatively small

sample size, tornado outbreaks, in which multiple tornadoes are documented in the same

general location on the same day, may be a source of bias to the spatial distribution,

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particularly east of the urban corridor. Figure 2.5 further highlights the spatial variability

that exists in tornado reporting by examining four county-level tornado trends. The four

counties include Weld County in north-central Colorado, which has seen the most tornado

segments (265) of any county in the U.S. since 1950; Adams County, a growing county that
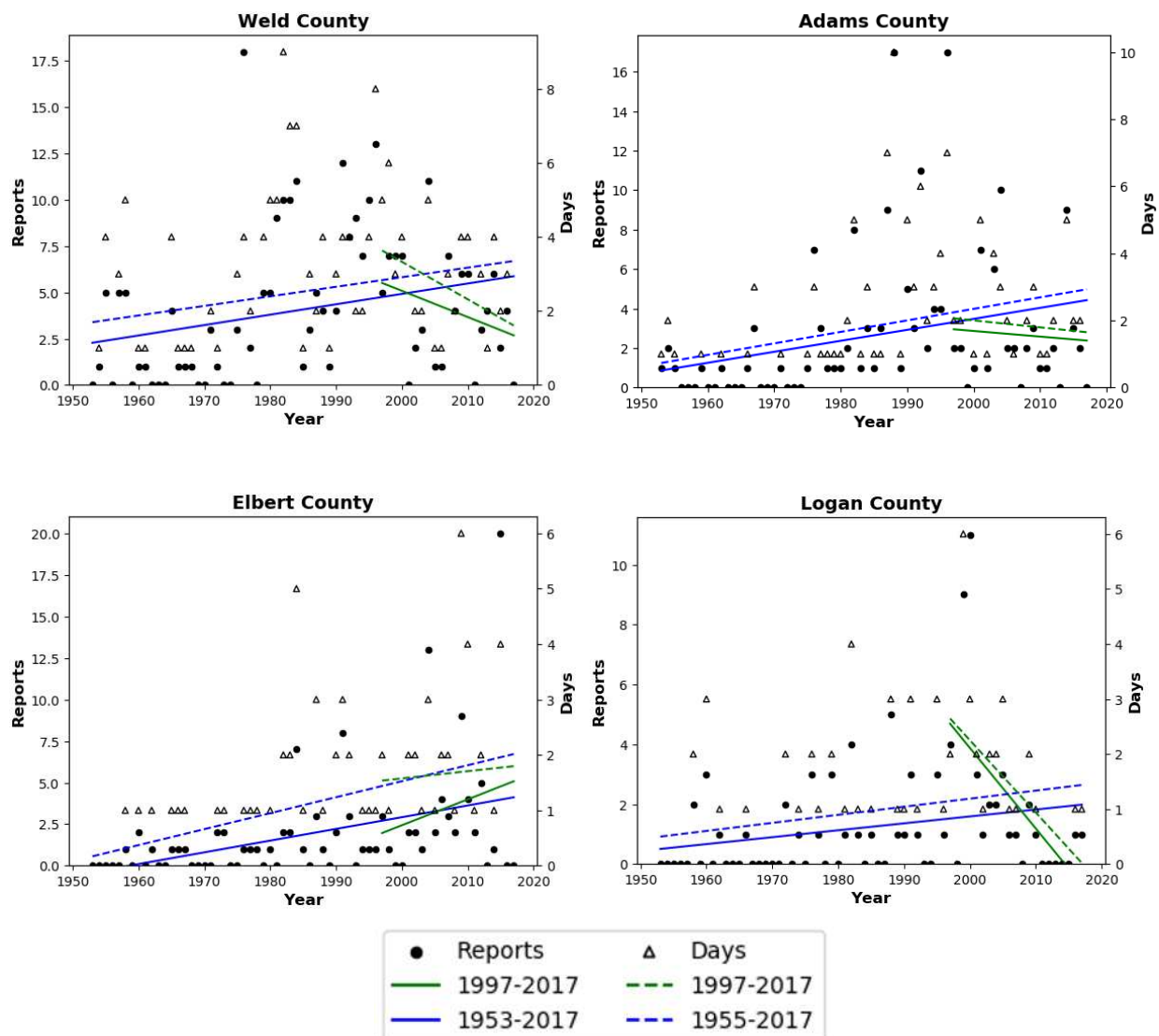
Fig. 2.5: Time series of tornado reports (solid dots) and tornado days (open triangles) for the periods 1953–2017 and 1997–2017 for four eastern Colorado counties. Linear trends for tornado reports (days) are shown in solid (dashed) lines.

houses the northern Denver suburbs and many rural areas, and which has seen the second-most tornado segments in the state (172) in the modern record; Elbert County, a rural county southeast of Denver which has the greatest increasing trend in tornado counts since 1997; and Logan County, another rural county east of Weld County which has the greatest decreasing trend in tornado counts since 1997. The two familiar time periods are represented, namely 1953–2017 and 1997–2017. Clearly, counties that have urban components (e.g. Adams) and those which are predominantly rural (e.g. Elbert) can both have increasing trends in tornado reports. Interestingly, although it is the top tornado county in the nation, Weld County shows a slightly decreasing trend in tornado counts and no trend in tornado days since 1997. Nearby Logan County has a sharp decreasing trend in tornado counts and days over this period, with several years of zero or one tornado report in the most recent decade. While there are too few reports to assess statistical significance in the respective trends, Fig. 2.5 at least reveals the intricacies of localized tornado trends as opposed to a composited trend over a much larger domain.

The NCEI Storm Events Database (available at https://www.ncdc.noaa.gov/stormevents/), provides the severe weather reports that are then archived in SPC's *Storm Data*, but also contains information on the source of severe weather reports since 1998. It is therefore intriguing to assess the distribution of tornado and hail reports among various sources in the eastern Colorado domain. More than thirty different storm report sources exist in the data records, which can be sorted into more general categories, as was the approach taken by Allen and Tippett (2015) in their assessment of sources of severe hail reports over the CONUS. Table 2.3 shows the sources of eastern Colorado tornado reports for the period 1998–2017. Unsurprisingly, the

Table 2.3: Sources of eastern Colorado tornado reports for the period 1998–2017. General categories are presented in the leftmost column, and their included subcategories are given in the second column.

SOURCE CATEGORY	INCLUDED CATEGORIES	REPORTS	%
Trained Spotter	Airplane Pilot, Meteorologist (Non-NWS), Trained Spotter	335	43.0%
Storm Chaser	Storm Chaser	167	21.4%
Law Enforcement	Law Enforcement	100	12.8%
Public	General Public	50	6.4%
NWS Employee	NWS Employee (Off Duty)	40	5.1%
Emergency Management	911 Call Center, Emergency Manager	30	3.9%
NWS Storm Survey	NWS Storm Survey, Official NWS Observations	11	1.4%
Unknown	Unknown (Missing)	9	1.2%
Government Official	County Official, Government Official, State Official	8	1.0%
Amateur Radio	Amateur Radio	7	0.9%
Broadcast Media	Broadcast Media	6	0.8%
Fire/Rescue	Fire Department/Rescue	6	0.8%
Newspaper	Newspaper	5	0.6%
Federal Agencies	Department of Highways, Other Federal Agency, Park/Forest Service, Post Office	4	0.5%
Social Media	Social Media	1	0.1%
Weather Station	ASOS, AWOS, COOP Observer, COOP Station, Mesonet	1	0.1%

majority of tornadoes are reported by trained spotters who are in the area where the tornado occurs. The second highest category is storm chasers, who account for 21% of tornado reports. The lack of obstructions to sight also allows tornadoes to be observed and reported much more easily across eastern Colorado relative to cities and forested areas.

Thus, despite the low number of residents across eastern Colorado (which leads to only 6.4% tornado reports contributed from the general public), the population here effectively booms during days in which there is a tornado risk, as storm chasers flock to the area and are able to document tornadoes that occur. As noted by an anonymous reviewer, the effect of storm chasers may also be influencing the relative maximum of tornado reports near the town of Lamar in southeastern Colorado (Fig. 2.4c-d), as this being the largest town for many miles caters well to storm chasers who descend on the area during a threat of severe weather. It should be noted that storm chasers can be documented in other categories as well, such as public and trained spotters (Allen and Tippett 2015), so the actual percent contribution of storm chasers may be higher. Other nontrivial sources of tornado reports across eastern Colorado include law enforcement, NWS meteorologists, and emergency managers. It is interesting to note that despite the rising popularity of promoting weather on social media in recent years, only one tornado report in the database is attributed to social media. This tornado, which occurred near the Flagler Airport in July 2016, was determined to be an EF0 landspout from a picture posted on Twitter that was obtained by the NWS. This is not to say that social media does not play a role in tornado reporting, and reference is even made to a social media post in reports attributed to other sources. Further, if a social media post is seen by a spotter or meteorologist before it is received at a local WFO, it may get catalogued as coming from a different source, or alternatively it may get catalogued as "general public" rather than "social media" (R. Cox, personal communication). Nevertheless, it is safe to say that most tornado reports across eastern Colorado are gathered from trained spotters and storm chasers. As will be seen in Section 4, the ranking of sources contributing to hail reports is not the same.

As a final piece of the eastern Colorado tornado climatology, analysis is presented on the length of the tornado season, that is, the number of days in a calendar year between first and last reported tornadoes. Table 2.4 lists these statistics for tornadoes (top) and severe hail (bottom, to be discussed in Section D) for the period 1997–2018 and also the two halves of that period separately (1997–2007 and 2008–2018). The year 2018 has been included in this analysis to provide two periods of equal length and to show a

Table 2.4: Length of the eastern Colorado tornado and hail seasons. Tornado seasons are categorized by (E)F0+ and (E)F1+ tornado reports, while hail seasons are categorized according to severe (1.0"+) and significant (2.0"+) hail reports. Three different periods are tabulated, as well as the average dates of the first and last respective reports during each period.

	1997-2018		1997-2007		2008-2018	
Hail Diameter	1"+	2"+	1"+	2"+	1"+	2"+
LENGTH OF SEASON	166	105	175	111	157	101
EARLIEST REPORT	17-Apr	7-May	12-Apr	7-May	22-Apr	7-May
LAST REPORT	30-Sep	20-Aug	4-Oct	26-Aug	26-Sep	14-Aug
Tornado Magnitude	(E)F0+	(E)F1+	(E)F0+	(E)F1+	(E)F0+	(E)F1+
LENGTH OF SEASON	134	73	141	78	128	75
EARLIEST REPORT	24-Apr	22-May	24-Apr	27-May	24-Apr	15-May
LAST REPORT	5-Sep	6-Aug	12-Sep	13-Aug	29-Aug	29-Jul

continuation of the overall trend. Figure 2.6a shows a time series (with linear regression line) of the length of season, and Fig. 2.6b shows time series (with linear regression lines) of the earliest and latest annual tornado reports for the period 1997–2018. It is seen that the (E)F0+ (i.e. all tornadoes) season is on average trending shorter in the past 20 years, due almost entirely to an earlier end to the season of roughly 15 days when comparing the trend line value in 1997 to that in 2018. In fact, the most recent tornado season at the time

of writing (2018) was only 79 days long, which was the second shortest (E)F0+ season in the modern record and the shortest since 2001. A similar shortening is noted when only (E)F1+ tornadoes are considered, again due mostly to an earlier end to the season. The average start of the (E)F1+ tornado season in the 2008–2018 period, however, is earlier than that of the 1997–2007 period by about 12 days. It should be noted that there were no (E)F1+ tornadoes in the domain in 2011, and 2018 (E)F1+ values are not included due to the tornado reports being preliminary at the time of writing. Student's t-tests and non-parametric Mann-Kendall tests were performed on these time series, but none of the trends were found to be significant at the 95% confidence level. While various reasons could be surmised as to the reason for the patterns seen in the length of the eastern Colorado tornado season, this will be left as future work.

To summarize, eastern Colorado has consistently experienced tornadoes since the modern data record began. Most of these tornadoes are weak, owing to both the local meteorological environment and the lack of structures to damage over the eastern Plains, but significant and deadly (E)F3 tornadoes have occurred in the state's history. Tornado counts and days trends are generally slightly downward since 1997, though not statistically significant, show little change in volatility, and have large variations between counties. The other major severe weather hazard in Colorado has substantially different climatological patterns.
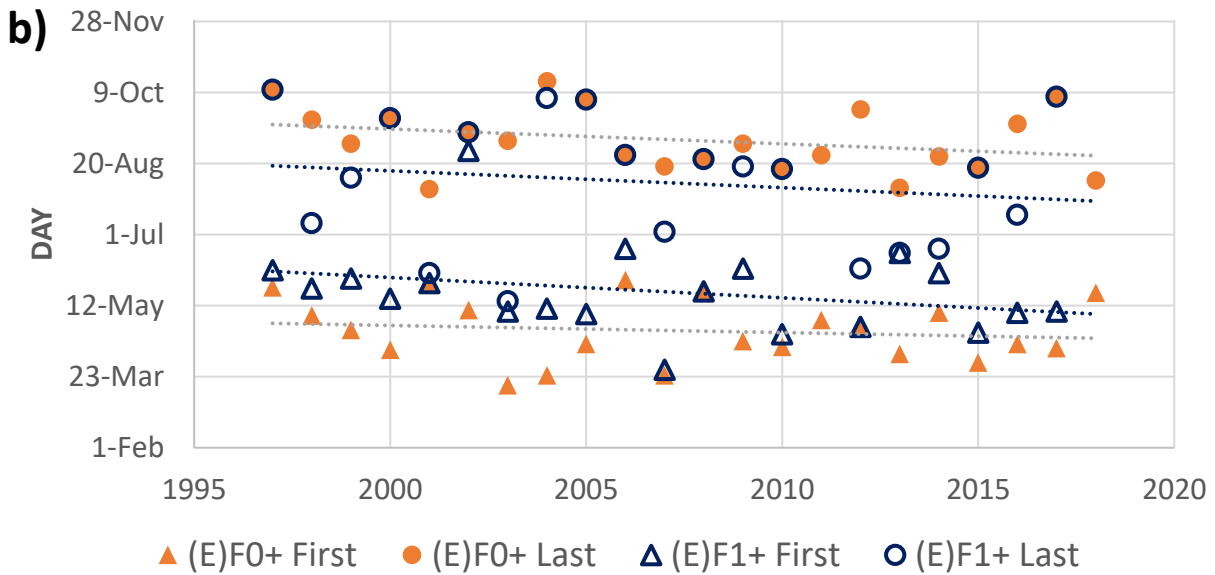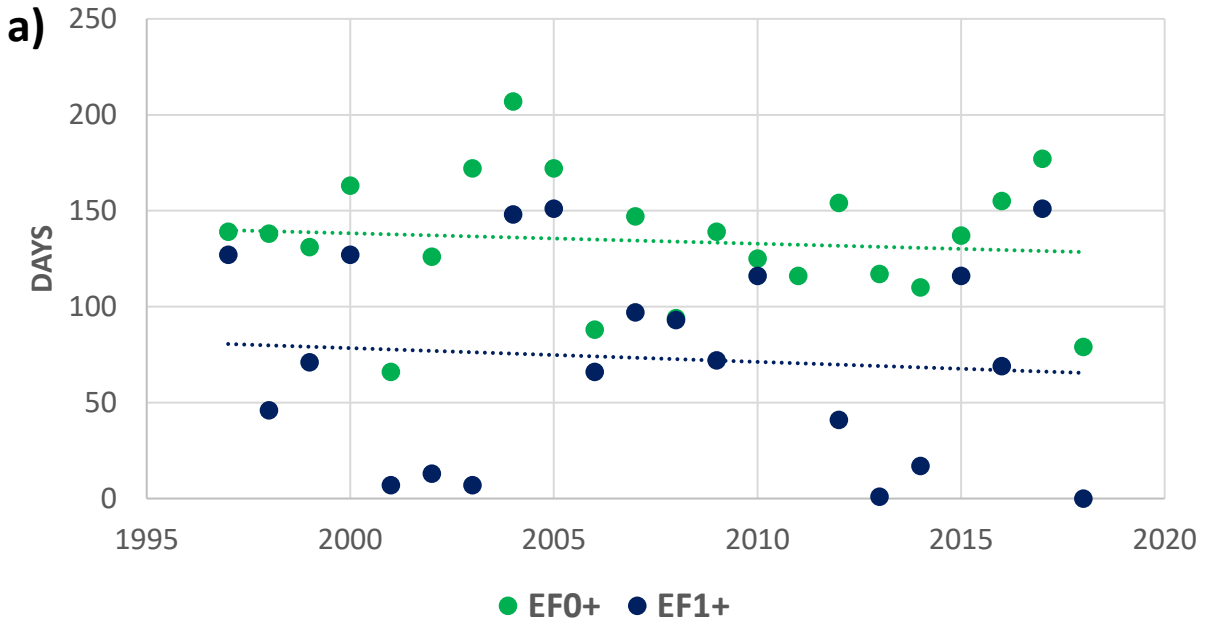
Fig. 2.6: (a) Time series of length of tornado season for the eastern Colorado domain for the period 1997–2018. All tornadoes (i.e. (E)F0+) are shown in green, and (E)F1+ tornadoes are shown in blue, along with their respective linear trend lines. (b) Time series of the date of the first and last (E)F0+ tornado reports (green, filled markers), and date of first and last (E)F1+ tornado reports (blue, open markers), along with respective linear trend lines, for the same period and domain.

4. Eastern Colorado Severe Hail Climatology

Severe hail reports are the most frequent among the severe weather hazards in eastern Colorado. Figure 2.7 shows the time series of severe hail counts and days for the two periods 1955–2017 and 1997–2017, partitioned by hailstone diameter, where a severe hail day is defined as a day in which at least one hailstone that exceeds the particular size threshold is reported. The linear trends are also shown in Fig. 2.7 and reveal that severe hail reports have been increasing across the domain over time, independent of size threshold. In fact, each of the size threshold trends for the period 1955–2017, as well as the 25.4-mm time series for the period 1997–2017, are statistically significant at the 95% confidence level, according to both Student t-tests and Mann-Kendall tests. As with tornadoes, this upward trend is influenced by non-meteorological factors, such as the increasing public awareness and interest in measuring hail, better documentation practices, and increasing population across the Front Range. While not as pronounced as in the tornado time series, a jump in hail reports is seen in the mid-1990s as a result of the expanding Doppler radar network. A greater inhomogeneity is seen after 2010, when the SPC threshold for severe hail was raised from 19.1 mm to 25.4 mm. The effect of this change is clearly seen in Fig. 2.7b, as almost all 19.1-mm+ hailstones reported since 2010 are also of the 25.4-mm+ variety. That is not to say that 19.1-mm hail is suddenly disappearing, but as reported by Allen and Tippett (2015), people are now more likely to report a hailstone as 25.4 mm to align with the SPC severe threshold. The upward trends also hold across all size thresholds for severe hail days (Fig. 2.8), and all of the 1955–2017 trends (Fig. 2.8a) are statistically significant at the 95% confidence level according to both Student t-tests and Mann-Kendall tests. In the more recent period (Fig. 2.8b), the numbers
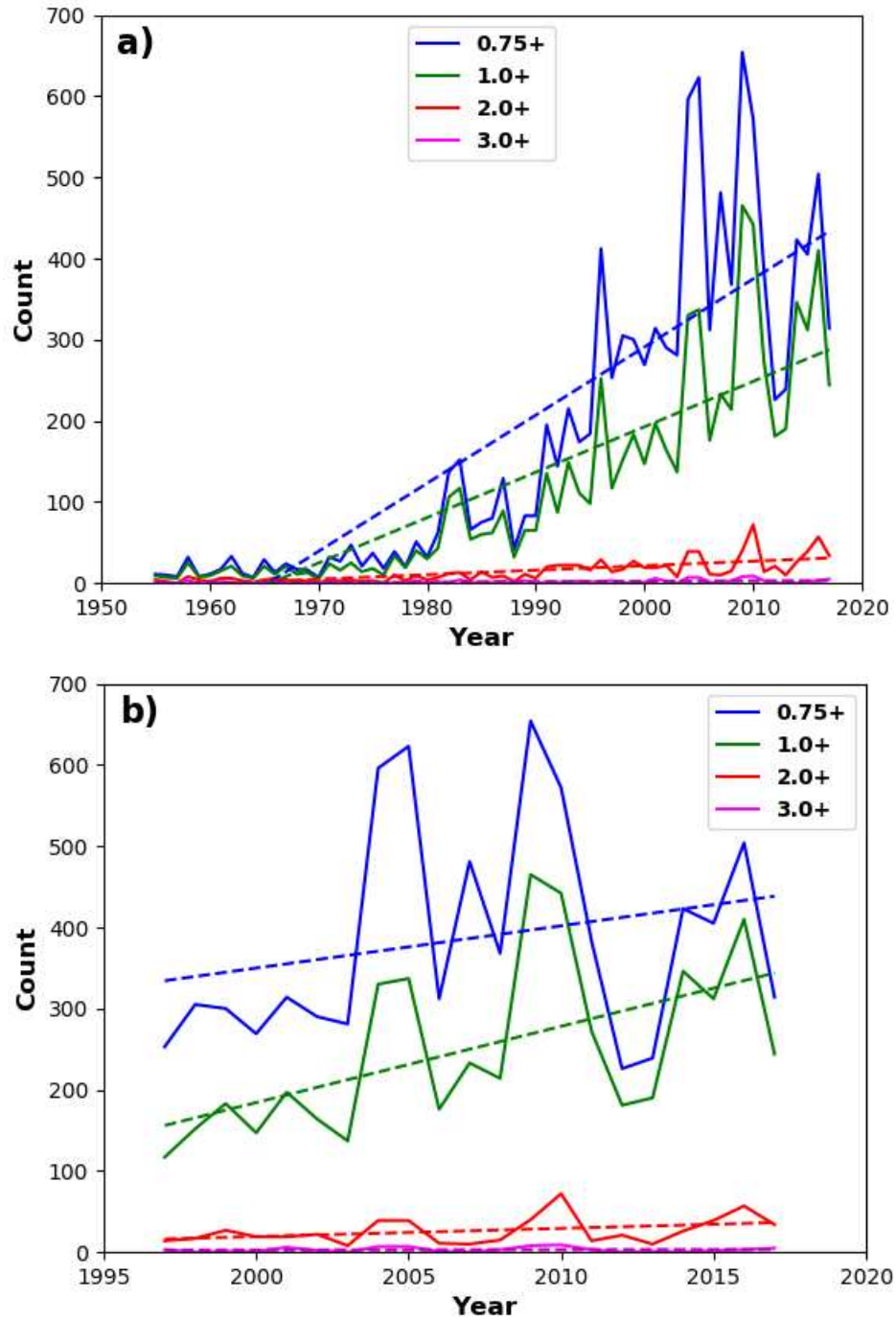
Fig. 2.7: Trends in eastern Colorado severe hail reports for the periods (a) 1955–2017 and (b) 1997–2017, partitioned by hailstone diameter.
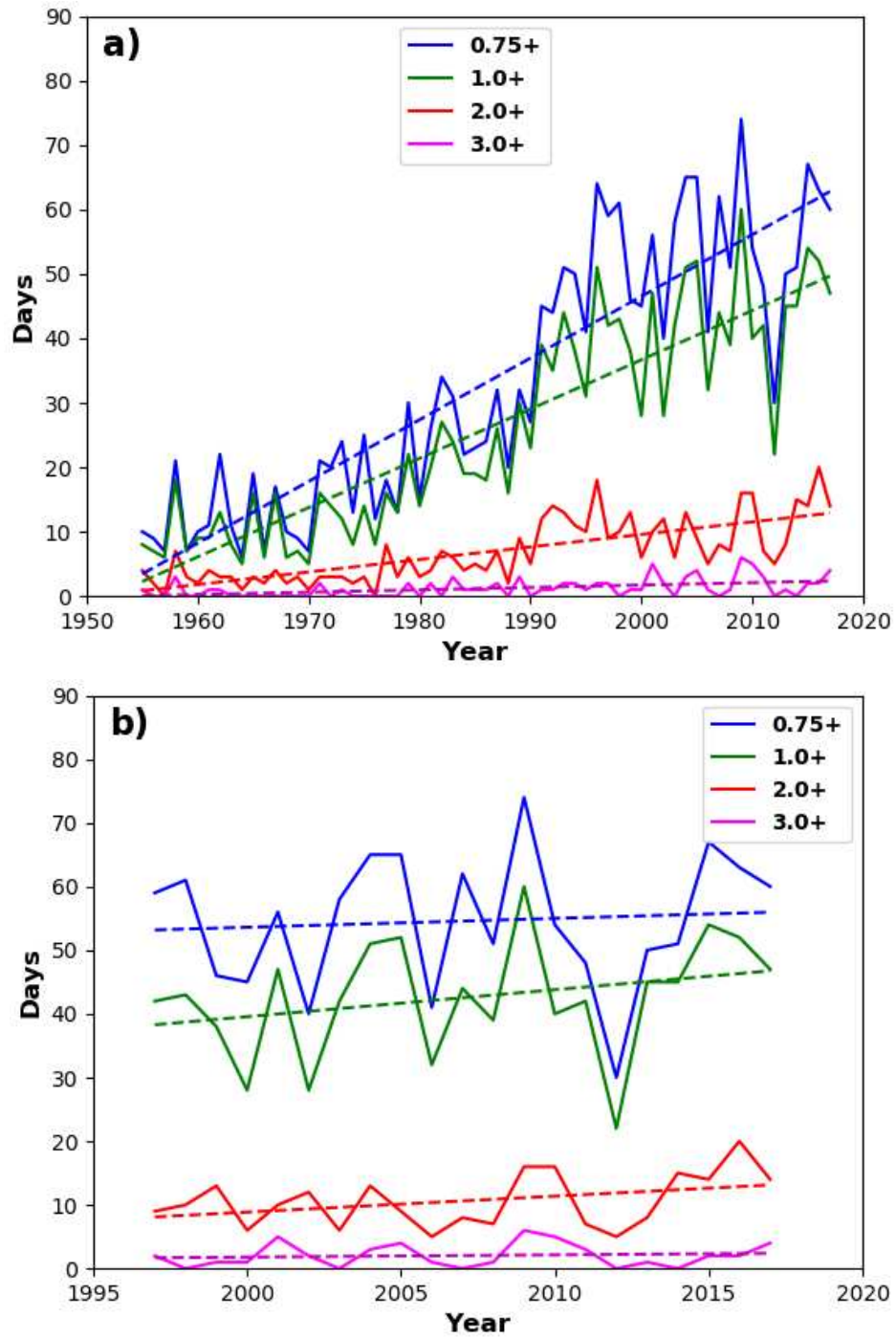
Fig. 2.8: As in Fig. 2.7, except for severe hail days; that is, days in which at least one hailstone of the given diameter was reported.

of 25.4-mm+, 50.8-mm+, and 76.2-mm+ severe hail days across eastern Colorado are also increasing, although none of the trends are significant at the 95% confidence level. Nevertheless, the upward trend in 25.4-mm+ hail days is notable because the national record shows no trend in severe hail day thresholds since 1997 (Allen and Tippett 2015). In 2018, which is not represented in the trends in Figs. 2.7-2.8, a record of ten 76.2-mm+ hailstones were reported over seven different days (Childs and Schumacher 2018), adding to the recent trends of increasing hail reports and hail days of these larger sizes.

Another metric by which to assess hail reports and days is the fraction of severe hail that is either significant (50.8 mm+) or in excess of 76.2 mm. Figure 2.9 shows these 50.8-mm+ and 76.2-mm+ fractions as percent contributions for reports (Fig. 2.9a) and days (Fig. 2.9b) over the period 1997–2018, along with linear regression lines. The percent contribution of 50.8-mm+ reports and 76.2-mm+ days show increasing trends over time, and the percent contribution of 76.2-mm+ reports has no trend. The percent contribution of 50.8-mm days has a slight decreasing trend, but the 43% value in 2002, which contributes to the downward slope, came in the year of least number of severe hail days over this period (28), and the twelve 50.8-mm+ hail days in 2002 was not abnormally high. Large variability is present in these metrics which precludes any statistical significance in the trends, although it is interesting to note that the highest values of every fractional metric except 50.8-mm+ hail days were seen in the year 2018. In fact, 20.1% of all severe hail reports in 2018 were at least 50.8 mm, and 3.0% were at least 76.2 mm, both of which either tied or eclipsed state records for the period since 1997 (Childs and Schumacher 2018). In addition, 27% of all severe hail days in 2018 included at least one 50.8-mm+ report, and a new state record of 14% of severe hail days included at least one 76.2-mm+
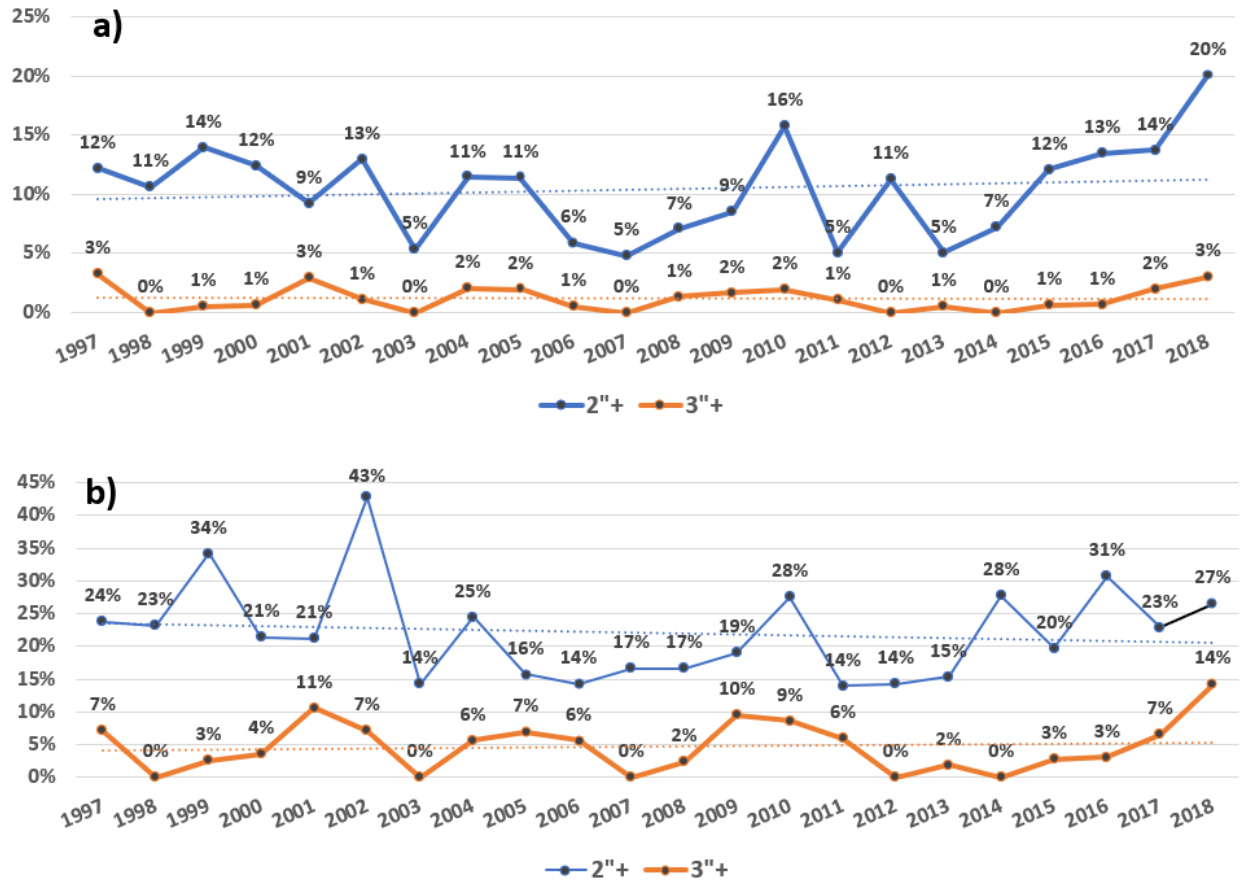
Fig. 2.9: Time series of percent contributions of 2 in+ (50.8-mm+) and 3 in+ (76.2-mm+) eastern Colorado hail (a) reports and (b) days for the period 2009–2018, with 2018 totals in bold bars.

report (Childs and Schumacher 2018). Increasing human exposure to hail storms, particularly along the Front Range, could be contributing to increasing fractional percentages over time, although approximately half of the sixty-six 50.8-mm+ hail reports in 2018 were located in rural areas.

Severe hail volatility is computed in the same way as tornado volatility in Section 3, with results presented in Table 2.2 comparing two recent decades. Unlike tornadoes, 25.4-mm+ and 50.8-mm+ severe hail report volatilities show a sizeable increase in the 2008–

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2017 decade. Increasing volatility is also noted for 25.4-mm+ and 50.8-mm+ severe hail days. While the 76.2-mm+ category shows muted volatility changes, there are very few reports of this diameter to begin with. Increasing volatility does not say much about changes in numbers of hail reports and days, but rather a greater expected range of the annual number of hail report counts and days in the 2008–2017 decade compared to the 1998–2007 decade, albeit the variability of the record precludes any statistical significance in the year-to-year differences for each period.

As already emphasized, hail reporting is subject to population bias, and this is no different for the eastern Colorado domain. In the same format as Fig. 2.4 for tornadoes, Fig. 2.10 presents the spatial distribution of severe hail reports, sorted by diameter, for the two periods of interest (1955–2017 [Figs. 2.10a-b] and 1997–2017 [Figs. 2.10c-d]). The point coordinates of the hail reports are shown in Figs. 2.10a and 2.10c, while smoothed versions are shown in Figs. 2.10b and 2.10d. It is immediately apparent via inspection of Fig. 2.10a,c that population bias is contributing to hail reporting. For example, cities along the Front Range such as Fort Collins, Denver, Boulder, Colorado Springs, and Pueblo can be overlain atop hail report clusters. Across the eastern Plains, hail reports form more linear patterns corresponding to Interstate highways and other major roadways. With relatively few paved roads across eastern Colorado, hail is more likely to be reported along major thoroughfares on which people drive. The smoothed plots in Fig. 2.10b,d are similar and affirm the higher number of hail reports along the Front Range cities, with local maxima in both periods near Denver, Colorado Springs, and Pueblo. As was the case for tornado reports, the least amount of hail reports is found in extreme southern Colorado, where very
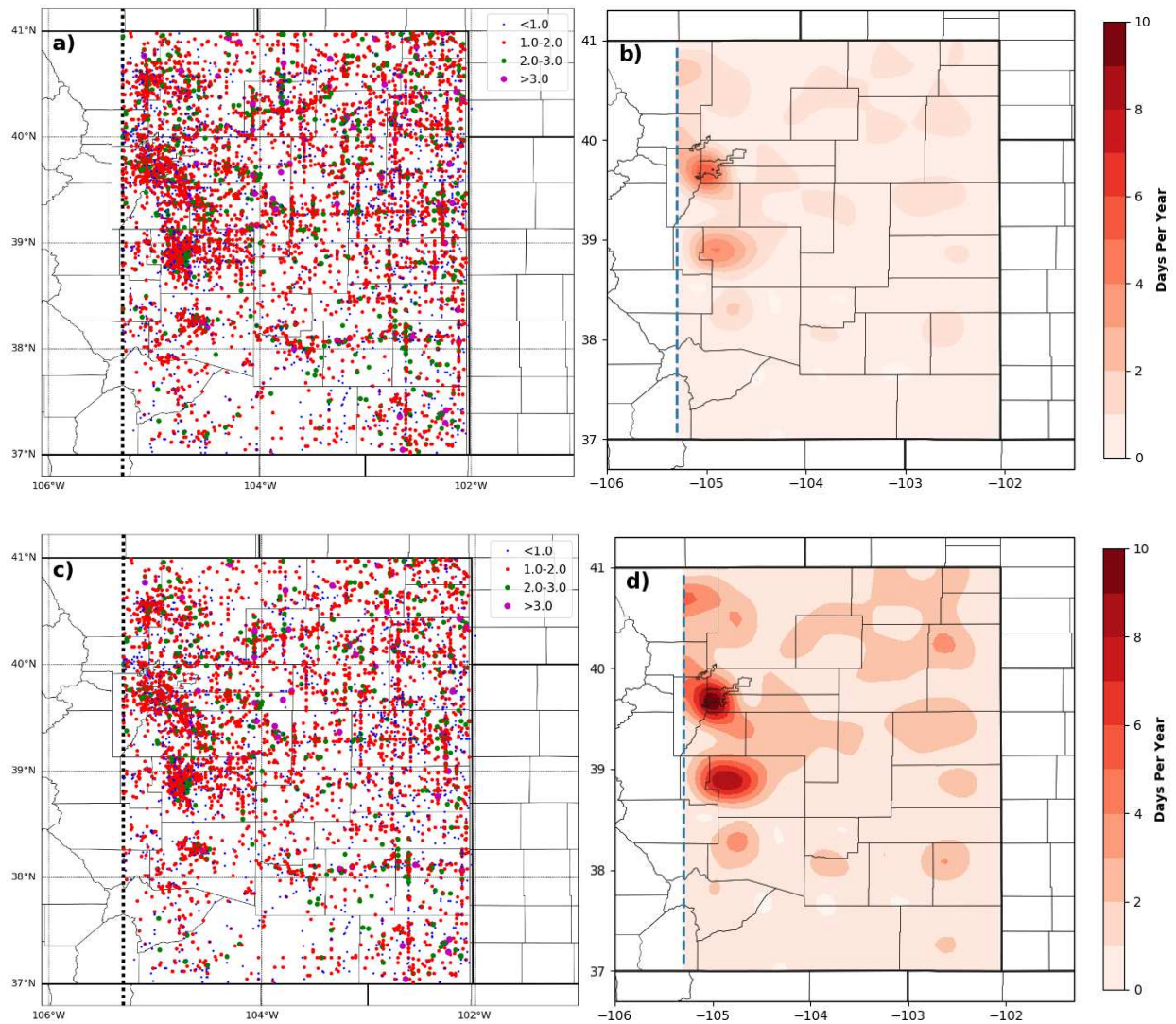
Fig. 2.10: Lat-lon severe hail reports (a,c) and gridded annual severe hail reports (b,d) for the periods 1955–2017 (a,b) and 1997–2017 (c,d). The gridded reports are smoothed from a 0.25° latitude X 0.275° longitude grid.

few people live; however, the relative maximum in tornado counts near Lamar in southeastern Colorado does not show up in severe hail reports, potentially reflecting the storm chasing preference for tornadoes in this area. The greatest concentration of hail reports is also shifted a bit further west than that of tornadoes, which has its maximum east of downtown Denver. Due to the high population bias leading to the concentration of

severe hail reports along the Front Range urban corridor, there are likely many severe

hailstones are going unreported because they are falling in places that are sparsely

populated. This result supports the large hail day deficits found in the Great Plains region

by Cintineo et al. (2012); that is, radar-based hail days subtracted from reports-based hail

days has a negative value due to missed reports in sparsely populated areas. Unlike

tornadoes, which can be rated posteriorly by matching damage indicators to a wind speed

range, accurately measuring and reporting hailstones before they melt requires a physical

presence, which is often not possible due to either lack of people in the vicinity or

dangerous weather conditions that prevent one from venturing outside to measure the

hailstone. Despite the non-meteorological influences on severe hail reports across eastern

Colorado, it is interesting to note that the maximum in Colorado lightning activity from

1996–2016 situated along and near the Palmer Divide (Hodanish et al. 2019) coincides

with a local maximum in severe hail reports just north of Colorado Springs over roughly the

same time period (Fig. 2.10d).

The influence of population dynamics on the eastern Colorado hail time series can

be seen at the county level by computing correlations between county population trends

since 2000 and county hail report and days trends since 1997 for twenty-six eastern

Colorado counties within the study domain. County populations are taken from the U.S.

Census Bureau and have been normalized by county land area. Pre-2000 county

population is only available in decadal increments, but from 2000 onward annual values

are available and therefore used here. The correlations between county population trend

and county hail reports and days trends are 0.425 and 0.441, respectively, both of which

are statistically significant. That is, counties in which population has been growing since

2000 also generally have a growing number of annual severe hail reports and severe hail days. Figure 2.11 displays this result graphically, with each county's population trend, normalized by area, and hail trend shown. Fourteen of the twenty-six counties had a positive population trend over this time period, out of which twelve had a positive hail report trend and eight had a positive hail days trend. Of the twelve counties that saw declining or stable population, all of which are in the rural eastern Plains, eight had decreasing trends in hail reports and ten had decreasing trends in hail days. Individual county intricacies can be noted in Fig. 2.11 as well that do not fit with the general correlation pattern. For example, El Paso County, home to Colorado Springs, has seen a growing population and by far the greatest increasing trend in severe hail reports, at just over two additional hail reports per year since 1997. However, the trend in hail days is slightly negative; that is, El Paso County is reporting more severe hail on fewer days. This of course does not hold in every year nor for every size threshold, as the 2018 calendar year contributed four 76.2-mm+ hail reports and three 76.2-mm+ hail days in El Paso County, both of which were county records (Childs and Schumacher 2018). Douglas County, which boasts the second-highest population trend, also had the greatest increase in severe hail days over the period. Yuma County, on the other hand, has the greatest decreasing trend in both hail reports and hail days of all counties analyzed, despite seeing a slight increase in population since 2000. Weld and Adams Counties, the top two counties in the state for tornado segments, show decreasing tornado counts since 1997 yet increasing severe hail counts over the same period. Elbert County, which has the greatest increasing tornado report trend since 1997, also has modest increases in severe hail counts and hail days over the same period, while at the same time increasing in population. Also

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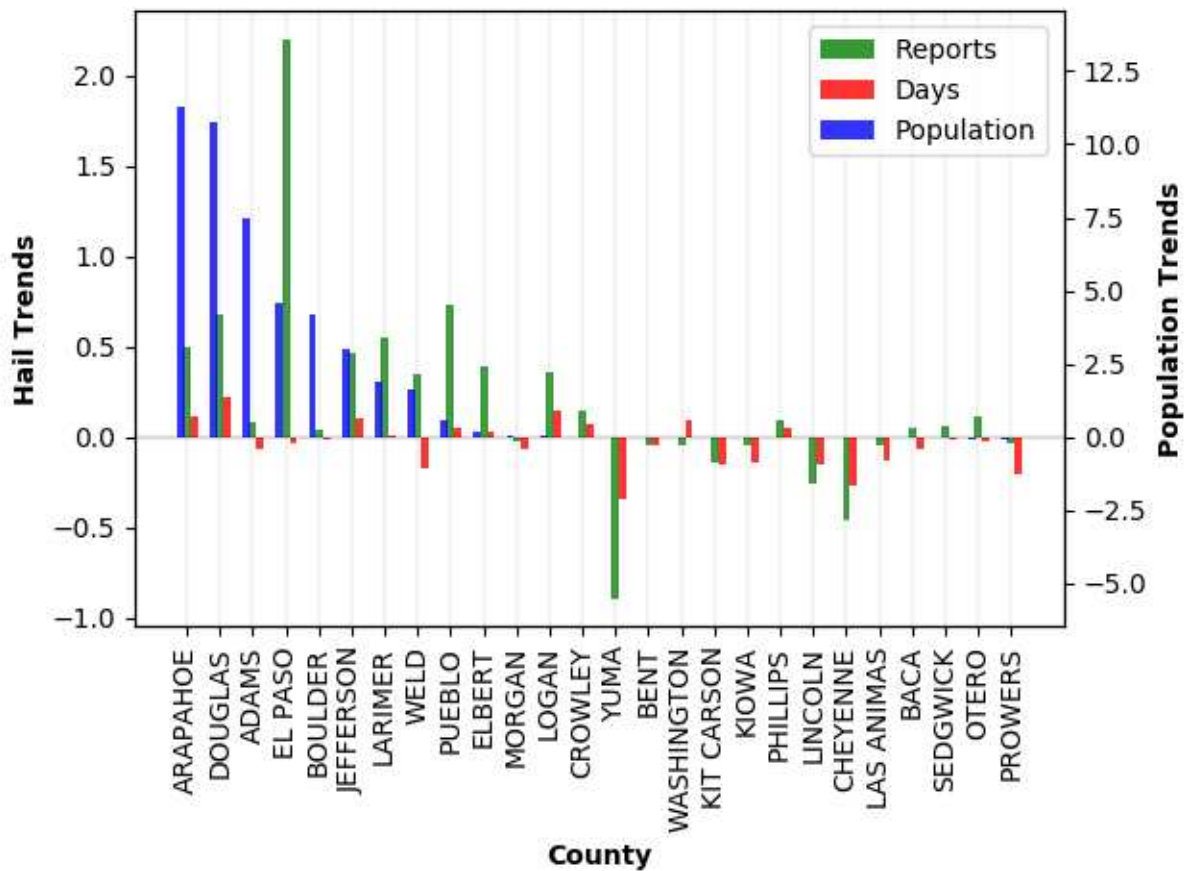
Fig. 2.11: Bar chart of county population trends (normalized by county area) for the period 2000–2017, and county severe hail report and days trends for the period 1997–2017, for twenty-six eastern Colorado counties within the study domain. The correlations between county population and severe hail reports and severe hail days are 0.425 and 0.441 respectively.

interesting to note are Cheyenne and Kiowa Counties: as reported in Section C, these counties are two of the most active for tornado segments when counties are normalized by area, but both counties also report decreasing trends in both severe hail reports and days. Again, population growth and smaller sample sizes preclude any statistical significance of the trends, but a stronger signal of population influence does exist on the eastern Colorado severe hail record relative to the tornado record.

The sources of severe hail reports shed further light on the population bias. Table 2.5 showcases the sources of severe hail reports for the period 1998–2017 across the eastern Colorado domain, using the NCEI Storm Events database. Two-thirds of all reports originate from trained spotters, a much higher proportion than for tornadoes (Table 2.3). This is largely due to a smaller contribution from storm chasers and law enforcement, as these sources only comprise 2.8% and 2.9% of reports respectively, as opposed to 21.4% and 12.8% of tornado reports. On the other hand, the general public reports a higher proportion of severe hail (12.4%) than for tornadoes (6.4%) across eastern Colorado. The linear nature of hail reports across the eastern Plains is most likely from commuters and/or storm chasers who are limited in their choice of paved roadways. Although trained spotters make up the brunt of all severe hail reports in eastern Colorado, Allen et al. (2015) also found that storm chasers are apt to report hail in the Great Plains in Spring due to lack of navigable roads and sparse population. Social media is again near the bottom of the hail report sources. Despite the wealth of hailstone pictures posted on social media outlets, more often than not, the official report for that particular storm comes from a trained spotter in the same area, or, alternatively, the source may get recorded as "general public" even though that person has posted a picture of the hailstone online. However, it should be noted that social media reports of hailstones have become very advantageous in rural areas that are hard to reach by car. Finally, it is interesting that some 238 severe hail reports (4.5%) are missing source information, compared to only nine tornado reports. This simply means that a hailstone was reported, but either the meteorologist documenting the report failed to enter the source or had conflicting information as to where and/or how the report originated (R. Cox, personal communication).

Table 2.5: Sources of eastern Colorado severe hail reports for the period 1998–2017. General categories are presented in the leftmost column, and their included subcategories are given in the second column.

SOURCE CATEGORY	INCLUDED CATEGORIES	REPORTS	%
Trained Spotter	Trained Spotter	3550	66.4%
Public	General Public	665	12.4%
Unknown	Unknown (Missing)	238	4.5%
Law Enforcement	Law Enforcement	154	2.9%
Storm Chaser	Storm Chaser	149	2.8%
Amateur Radio	Amateur Radio	143	2.7%
NWS Employee	NWS Employee (Off Duty)	112	2.1%
CoCoRaHS/SHAVE	CoCoRaHS, SHAVE Project	81	1.5%
Emergency Management	911 Call Center, Emergency Manager	76	1.4%
Weather Stations	ASOS, AWOS, COOP Observer, COOP Station, Mesonet	65	1.2%
Broadcast Media	Broadcast Media	39	0.7%
Government Official	County Official, Government Official, State Official	18	0.3%
NWS Storm Survey	Official NWS Observations	15	0.3%
Fire/Rescue	Fire Department/Rescue	12	0.2%
Federal Agencies	Department of Highways, Other Federal Agency, Park/Forest Service, Post Office	12	0.2%
Newspaper	Newspaper	9	0.2%
Social Media	Social Media	7	0.1%

Finally, a glimpse at the changes in the length of the eastern Colorado severe hail season is given in Table 2.4 (bottom) and Fig. 2.12. Table 2.4 (bottom) lists the total length as well as average calendar-day first and last severe and significant hail report for the period 1997–2018, and the two halves of that period. Figure 2.12 then presents time series of the length, starting date, and ending date, of the eastern Colorado severe hail season since 1997. There is an appreciable decreasing trend in both severe and significant hail

season length over this time period, though not statistically significant according to a Mann-Kendall non-parametric test. Specifically, the eleven-year average severe hail season length has declined from 175 days to 157 days from the period 1997–2007 to 2008–2018, and significant hail season length has declined from 111 days to 101 days over the same two periods. Most of the decrease comes on the tail end of the hail season. Comparing 2018 to 1997, the average last severe hail report of the year was approximately 25 days earlier, with significant hail reports ending approximately 14 days earlier (Fig. 2.12). As was the case for tornadoes, the year 2018 saw the shortest severe hail season in the modern data record for the state of Colorado at only 113 days, thanks to a particularly early end to the season on 21 August. In fact, not since 1995 had the last severe hail report in Colorado occurred in August. Figure 2.12 also reveals a trend toward an earlier first severe hail date since 1997, while the date of the first significant hail report has not changed much over time. While it is beyond the scope of this work to speculate as to the reasons for the shorter severe hail season, and specifically the trend toward an earlier end of the season, one major contributor to rainfall and convection in late summer across eastern Colorado is the Southwest Monsoon (Mock 1996, Colorado Climate Center). Therefore, a change or shunting of the monsoon annual cycle may serve to affect hailfall across the domain. Further investigation is warranted into this trend. Nevertheless, this finding is insightful when coupled with the previously-reported climatological trends, as it shows that even though the severe hail season across eastern Colorado is, on average, shorter in the more recent period, this period has also seen a slightly higher proportion of significant hail reports. In addition to the increasing trend in hail reports and days across the domain, the other critical attribute of the eastern Colorado hail climatology is population bias that,
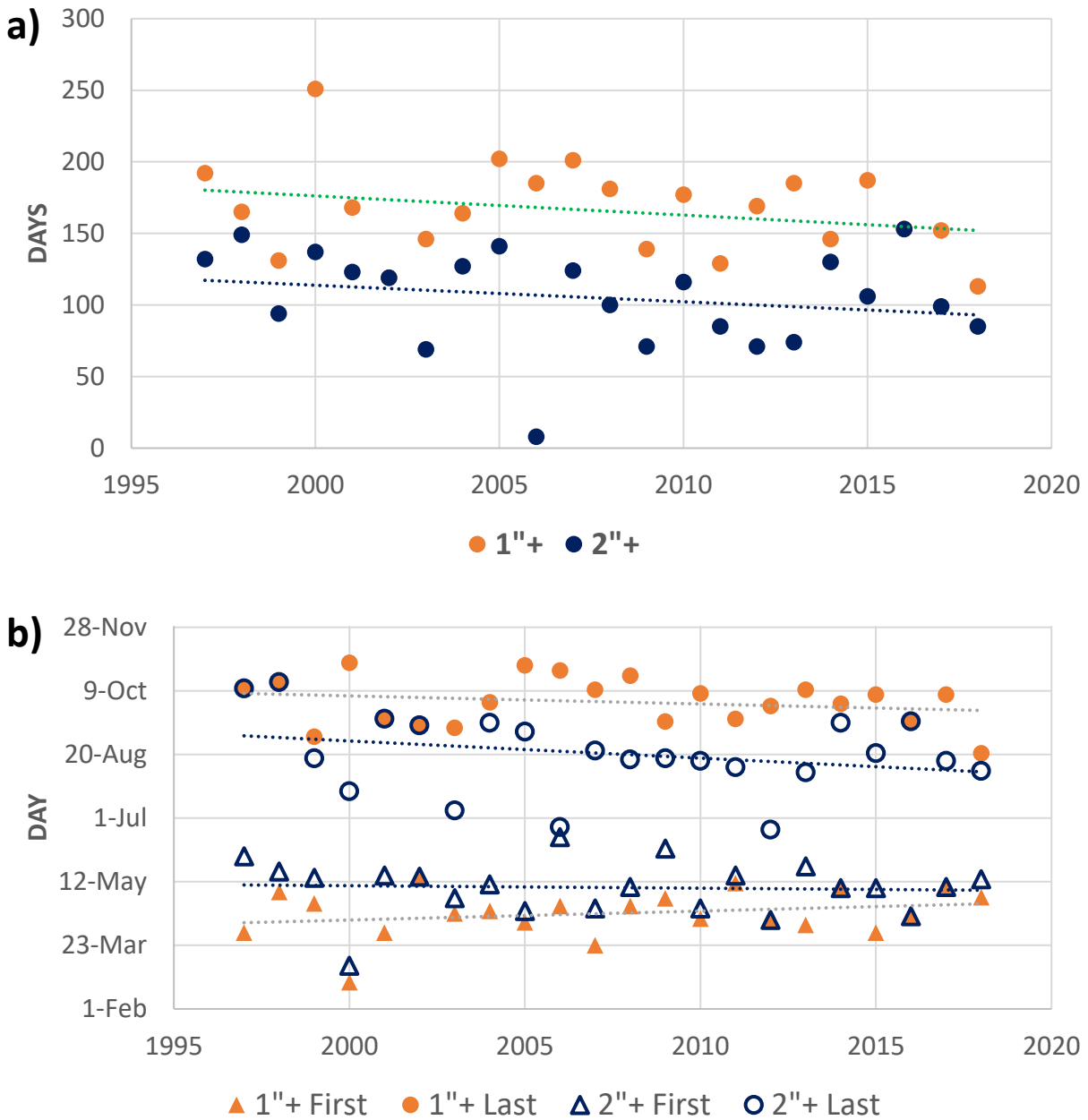
Fig. 2.12: As in Fig. 2.6, but for severe (green) and significant (blue) hail reports. Time series of total length of season in days (a) and date of first and last annual reports (b) are presented, along with respective linear trend lines.

although improving over time, continues to distort the hail record and influence both the temporal and spatial hail report patterns.

5. Convective Parameter Comparison

A rational inquiry in response to the tornado and hail trends presented herein is what meteorological conditions are associated with these phenomena and, relatedly, how might these conditions change in the future to promote amplified or reduced hazard occurrence. These questions will be addressed in Chapter 4 where projections of end-of-century frequency and spatial distribution of tornadoes and severe hail are considered. Here, a brief comparison of the environments associated with these hazards is ventured by analyzing convective parameters diagnosed at the times of tornado and severe hail reports and documented in the SPC Storm Mode database (Smith et al. 2012, Thompson et al. 2012). This database contains data of convective modes of tornado- and hail-producing storms, namely discrete, cell-in-line, cell-in-cluster, and quasi-linear convective system, for the period 2003–2015. Of interest in this work are the convective parameters paired with each hazard report for the applicable domain of eastern Colorado.

Box-and-whisker plots (Fig. 2.13) show distributions of nine parameter observations for the 423 tornado and 418 severe hail events within the eastern Colorado domain from 2003–2015 that have associated convective parameter data within the Storm Mode database. For the years prior to 2010, severe hail events include any hailstone greater than 19.1 mm in diameter. In general, the environments for severe hail across eastern Colorado align more closely with those associated with typical severe
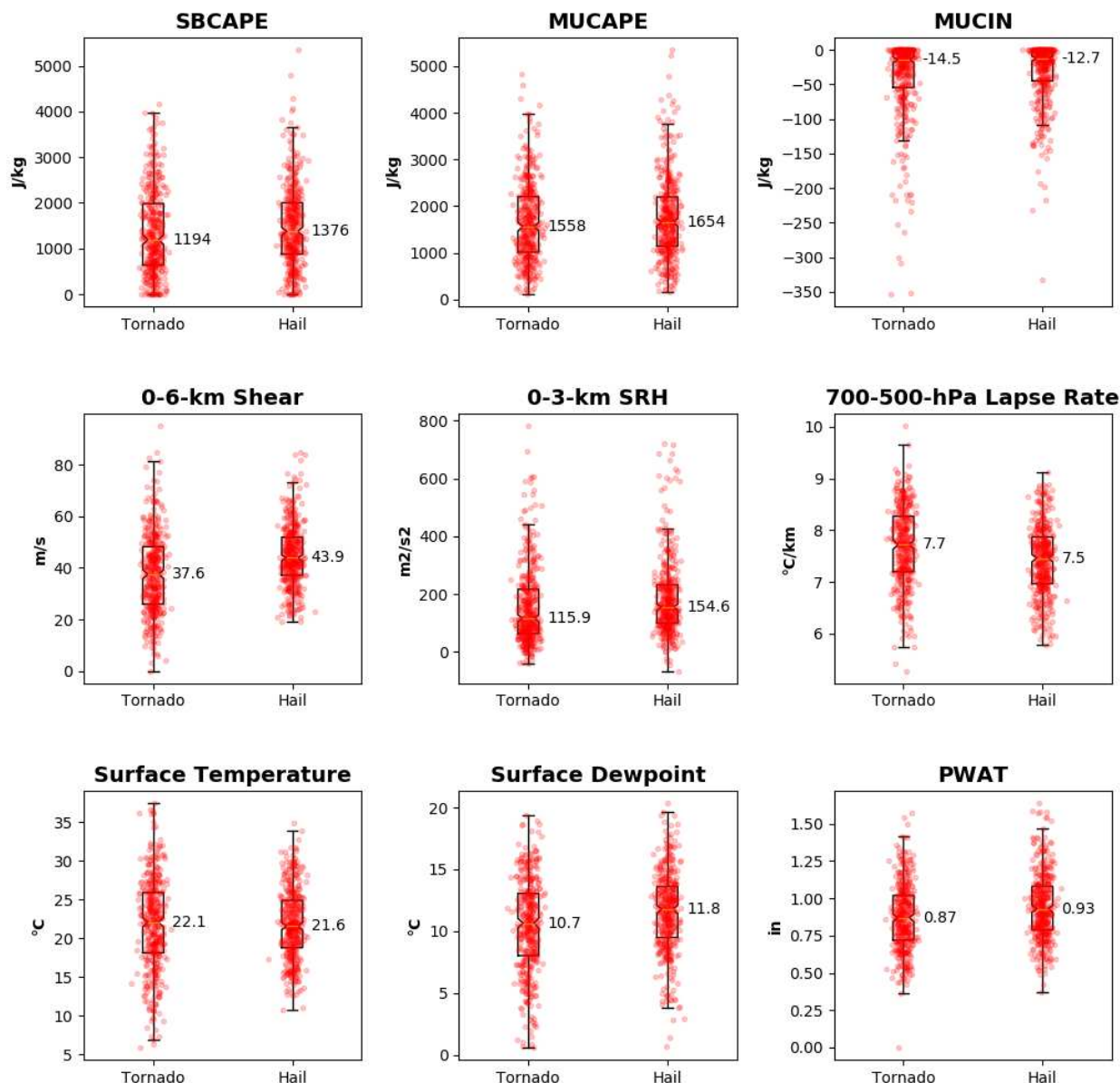
Fig. 2.13: Box-and-whisker distributions of convective parameters taken from the time and location of severe hail and tornado reports across eastern Colorado for the period 2003–2015, as contained in the Storm Mode database. The numbers represent the median of each distribution. The sample size is 423 tornado and 418 severe hail reports.

thunderstorms than do the tornado environments. Thermodynamically, severe hail

environments have higher SBCAPE and MUCAPE as well as smaller MUCIN, indicating

higher positive buoyancy and less inhibiting energy for convection. It should be stated, however, that the median CAPE values for both hazards are less than 2000 J kg^{-1}, which would not be considered alarming for severe weather environments further east. Severe hail environments are also characterized by much higher vertical wind shear and storm-relative helicity. As Brooks et al. (2009) showed that the product of MLCAPE and 0-6-km shear is a good metric for the likelihood of significant severe thunderstorms, the eastern Colorado severe hail events are in general reported under more conducive severe weather environments than are tornado events. The moisture variables of precipitable water and surface dewpoint are higher in severe hail events, perhaps not surprisingly considering that sufficient water vapor in the atmosphere is necessary for hail growth. Surface temperatures are slightly warmer in the median for tornado events, and there is very little difference in mid-level lapse rates between the two hazards. This analysis affirms characteristics of the eastern Colorado severe weather climatologies. For example, almost all tornadoes across the domain are weak, and in some cases are absent of a mesocyclone. On the other hand, it is not uncommon for hail events to produce giant hail stones, a result that requires an intense updraft, rotation, and enhanced moisture often indicative of supercells.

6. Summary and Conclusions

Tornadoes and severe hail storms are the two major severe weather phenomena that occur routinely across Colorado each year. In fact, the eastern half of the state is a local maximum in the frequency of both of these hazards across the U.S. Much work has been done to identify unique features of severe weather over eastern Colorado and the rest of the High Plains region, both in case study and broader dynamical contexts, but relatively

little work has been done to analyze climatological trends in tornadoes and severe hail. This study has presented the most comprehensive look at the frequency and geography of eastern Colorado tornadoes and severe hail, with analysis starting from the mid-1950s, but focused on 1997 to present, when tornado and severe hail data are more reliable. Documented problems with the quality of tornado and severe hail data are exposed in this localized study, including but not limited to a spike in (E)F0 tornadoes with the advent of Doppler radar in the mid-1990s and a population bias contributing to the upward trend in severe hail reports. In fact, severe hail reports are closely aligned with major population centers and roadways across eastern Colorado. In a mean sense, topography certainly plays a role in the spatial distribution of severe weather in Colorado, with tornado reports showing a maximum in north-central Colorado and severe hail reports concentrated right along the foothills. This study also finds that in general, the length of the tornado season across eastern Colorado is slowly declining along with their frequency of occurrence. On the other hand, although the length of the severe hail season is also decreasing over time (mostly due to an earlier end to the season), the number of severe hail reports over the period 1997–2017 is increasing at a statistically significant pace. In addition, the proportion of hail stones observed as significant and in excess of 76.2 mm has an increasing trend since 1997, with 2018 seeing record fractional percentages. The comprehensive climatology presented here for one of the most active tornado and severe hail areas in the country can be a worthy and helpful reference for both the local Colorado and national meteorological communities. Moreover, it motivates the rest of this doctoral study that aims to quantify risks from these hazards in a future climate.

CHAPTER 3: A REVIEW OF THE ANOMALOUSLY DESTRUCTIVE 2018 COLORADO HAIL

SEASON[3]

A. Background

While a climatological analysis of eastern Colorado hailstorms up to the year 2017

was given in Chapter 2, the following calendar year not only continued many of the trends

but featured new state records and extreme events from both meteorological and societal

perspectives that merit special investigation. This chapter will thus provide a brief case

study analysis of three hail events from 2018, as well as offer a potential environmental

explanation for the enhanced activity. This work was presented at the Severe Local Storms

Conference (Childs and Schumacher 2018) and motivated a broader publication for *The*

Conversation (Childs 2018).

For the period 1955–2017, Colorado saw an average of 177 severe hail reports (19

mm+) per year, and during a more recent 21-year period (1997–2017), when hail data has

been more reliable (Allen and Tippett 2015), Colorado has averaged around 250 severe

hail reports in excess of 25.4 mm.   Although large hail events are nothing new to

Coloradoans, the 2018 hail season does stand out as anomalous in many respects. The

complex interplay between the meteorological and societal influences of hailstorms were

on full display in 2018, with an abnormally high number of very large hail reports and days,

high-altitude hail reports, and an injury-producing storm at a popular tourist attraction.

These events will be highlighted as case study analyses in this chapter, as well as several

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[3] Adapted from Childs (2018) and Childs and Schumacher (2018b)

statistics and new state records set for both hail days and hail reports during 2018. A potential environmental explanation for the enhanced activity is also offered. The applications and take-aways from this hail season are many, and complement this doctoral study's focus on the forecasting and communication of these high-impact hail events.

B. Climatological Review

As in the national hail data record, Colorado has seen a consistent increasing trend since 1955 in both hail reports and hail days for all size thresholds (Figs. 2.7-2.8). Each size threshold trend in reports is statistically significant at the 99% confidence level, with 25.4-mm+ reports increasing at a rate of 5.6 reports per year. Likewise, each size threshold trend in hail days since 1955 is also significant at the 99% confidence level, with an increase of roughly 3 days per year for 25.4-mm+ hail days. When the time period is limited to 1997–2017, which comprises a more reliable data record, an increasing trend is still seen in both hail reports and hail days for all sizes. The only statistically significant trend during this 21-year period is for 25.4-mm+ hail reports, with an increase of almost ten more hail reports per year for this size threshold. Despite a lack of statistical significance in hail days trends since 1997, the increasing trends in the number of both 25.4-mm+ and 50.8-mm+ hail days stands in contrast to the national record, which shows no trend for these size thresholds since 1997 (Allen and Tippett 2015).

The main inhomogeneity present in severe hail data is that of population bias. This bias is of particular concern in the Colorado hail record due to the stark divide between the Front Range urban corridor and the rural landscape of the eastern Plains. Namely, a clustering of hail reports exists near cities and along major roadways (Fig. 2.10). The

overwhelming majority of severe hail reports are found along the Interstate 25 urban

corridor, yet in the western half of Colorado, where only about 5% of all the state's severe

hail is reported, clusters of reports are still seen in the populated areas such as Grand

Junction and Durango. It can therefore be inferred that at least part of the upward trend in

severe hail reports is due to population growth along the Front Range; simply put, where

more people live, more hail is reported. However, individual counties can show highly

variable trends in hail reports and hail days. Of note to the results contained in this chapter

is El Paso County, which houses the rapidly-growing Colorado Springs metropolitan area.

By far, El Paso County boasts the largest increasing trend in hail reports (+2.2 reports per

year), yet has a slightly decreasing trend in hail days (-0.03 days per year). In other words,

more hail is being reported in Colorado Springs and the surrounding areas of El Paso

County, but on fewer days. On the other hand, Yuma County (with a very marginal

increasing normalized population trend [+0.01]) has seen the greatest decreasing trend in

both hail reports and hail days.

C. 2018 Hail Season

1. Overall statistics

By several metrics, the 2018 calendar year was the most active hail year in Colorado

state history to-date. Ironically, though filled with destructive hail events, 2018 was

actually the shortest severe (25.4-mm+) hail season in Colorado since 1995. The year's first

severe hail report came on April 30, and the final report was documented on August 21, for

a hail season length of 113 days. When only significant hail reports are considered, where

significant refers to hailstone reports of 50.8-mm diameter or greater, the season stretched

from May 14 to August 7, for a total of 85 days. This shunted season follows a continuing

trend: since 1997, the length of the Colorado severe hail season has shortened by an average of 1.4 days per year, with an earlier end to the season as the primary driver of the trend for both size thresholds (Fig. 2.12). Figure 3.1 displays a time series of the 2018 Colorado hail season in two ways, with Fig. 3.1a showing the cumulative sum of severe hail reports over the year, and Fig. 3.1b showing the daily number of severe hail reports. Both plots also show the 1997–2017 average for reference. Figure 3.1a is particularly useful in revealing the late start and early end to the hail season. After a late start, the 2018 severe hail season more or less followed the 20-year average until the second half of July, where a very active hail period commenced and lasted through the first half of August. Fig. 3.1b shows several days of heightened severe hail activity during this period, and two of the major events within this time are detailed below. Tables 3.1 and 3.2 give the 2018 monthly distribution of severe hail reports and hail days, respectively, partitioned by size threshold. Tables 3.1 and 3.2 also show the 1997–2017 monthly averages for severe hail. A greater-than-average number of severe hail reports were made in the months of May, June, July, and August 2018, whereas March, April, September, and October reports were practically non-existent (Table 3.1). The number of monthly 2018 severe hail days were all near their respective average expect for May, which saw nearly double the expected number of severe hail days (Table 3.2). Overall, in both hail reports and hail days, 2018 was a bit above average but not exceptional. Rather, as Fig. 3.2 depicts, the 2018 totals of 328 25.4-mm+ hail reports (Fig. 3.2a) and 49 hail days (Fig. 3.2b) fit with the natural year-to-year variability that has been present over the last decade (as shown in Fig. 3.2) and ultimately since the start of the Doppler Radar era in 1997. The year 2009 holds the state record for

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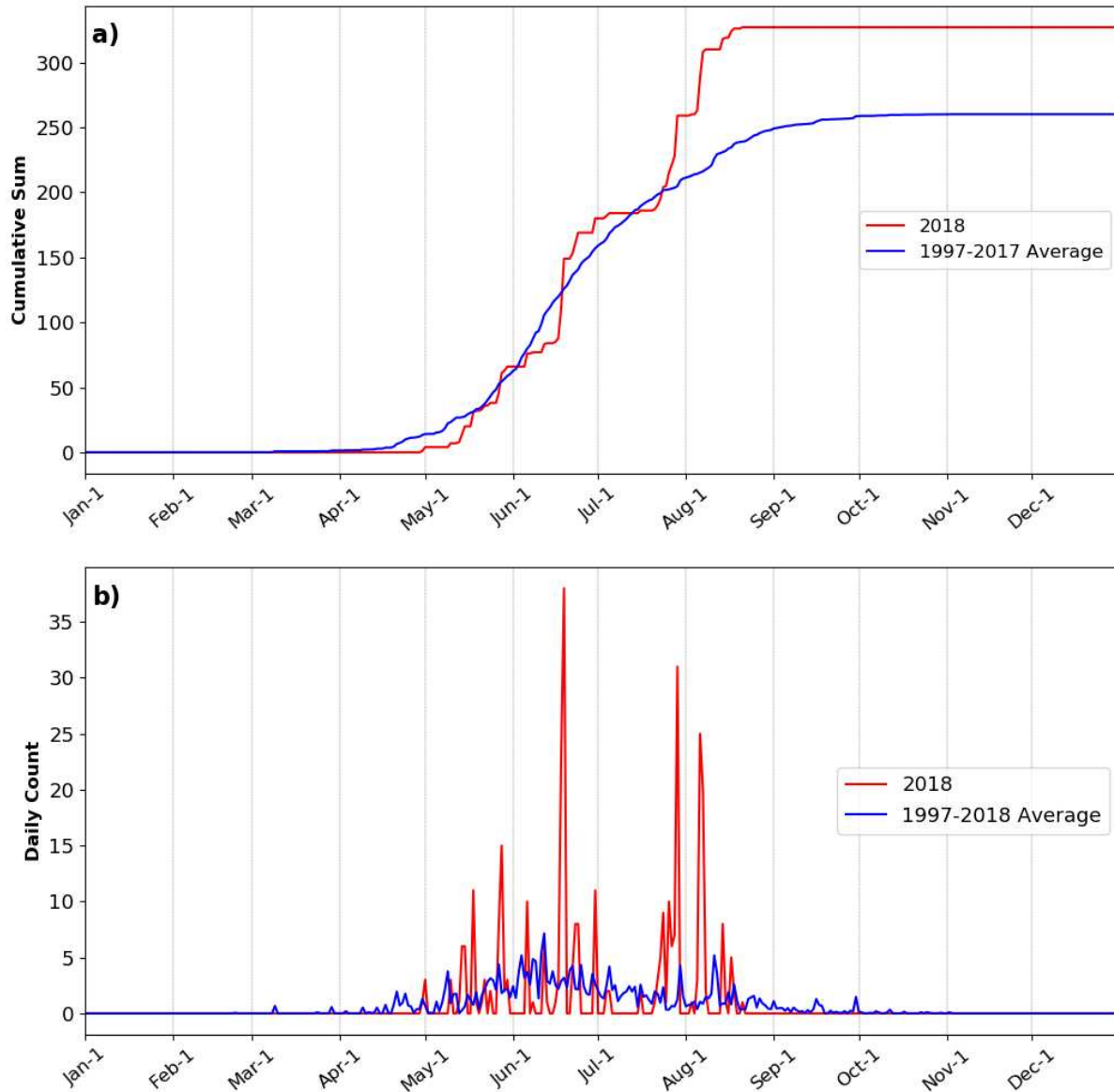
Fig. 3.1: (a) Cumulative sum of severe hail reports and (b) Daily count of Colorado severe hail reports for both 2018 and the 1997–2017 state average.

most severe hail reports (481), and 2015 holds the record for most severe hail days (71).

Note that 2009 only ranks 3rd in number of severe hail days, and 2015 ranks 6th in number

of severe hail reports over the past ten years, proving that a high number of severe hail

reports does not necessarily equate to a high number of severe hail days.

Table 3.1: 2018 monthly severe hail reports in Colorado.

Month(s)	1″+	1″+ Avg.	2″+	3″+
March	0	1.3	0	0
April	1	12.7	0	0
May	64	48.9	4	0
June	114	96.1	28	5
July	79	52.2	21	3
August	68	38.0	13	2
September	0	9.6	0	0
October	0	1.3	0	0
Total	**328**	**260**	**66**	**10**

Table 3.2: 2018 monthly severe hail days in Colorado.

Month(s)	1″+	1″+ Avg.	2″+	3″+
March	0	0.1	0	0
April	1	2.0	0	0
May	14	7.5	2	0
June	12	13.0	5	4
July	12	10.0	3	2
August	10	8.7	3	1
September	0	2.5	0	0
October	0	0.7	0	0
Total	**49**	**44.5**	**13**	**7**

Where the 2018 hail season does stand out is in terms of the proportion of severe hail reports that were of the significant (50.8-mm+) variety. Figure 3.2 reveals that the state reported sixty-six 50.8-mm+ hailstones in 2018, which ranks second all-time, and ten

a)

Legend: ■ 1"+ ■ 2"+ ■ 3"+

Year	1"+	2"+	3"+
2009	481	41	8
2010	457	72	9
2011	276	14	3
2012	186	21	0
2013	197	10	1
2014	359	26	0
2015	322	39	2
2016	423	57	3
2017	247	34	5
2018	328	66	10
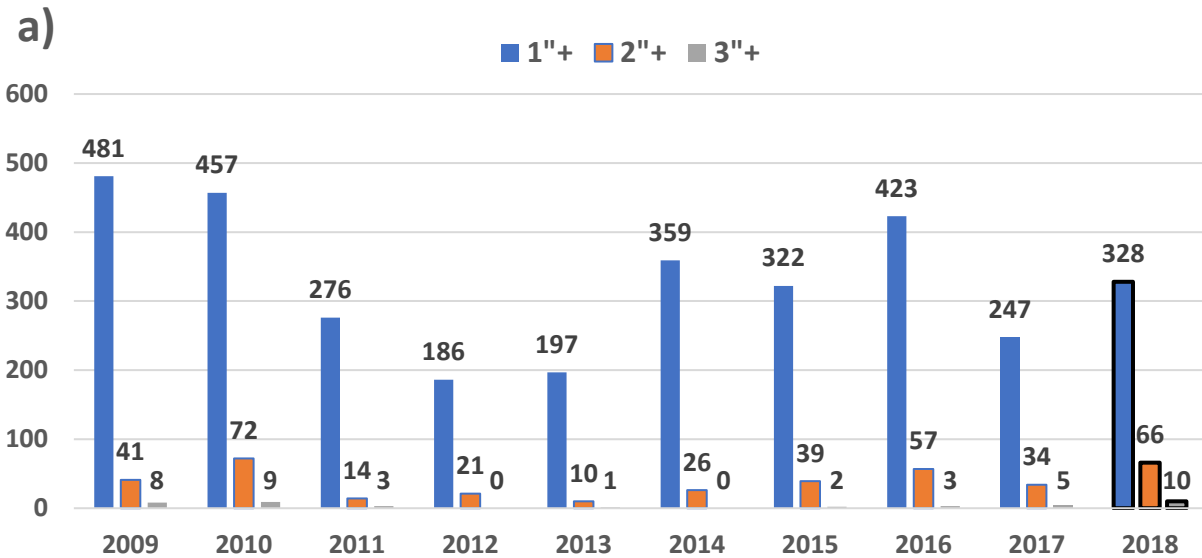
20-Year Averages: 250 (1"+), 46 (2"+), 3 (3"+)

b)

Legend: ■ 1"+ ■ 2"+ ■ 3"+

Year	1"+	2"+	3"+
2009	63	16	6
2010	58	16	5
2011	50	7	3
2012	35	5	0
2013	52	8	1
2014	54	15	0
2015	71	14	2
2016	65	20	2
2017	61	14	4
2018	49	13	7
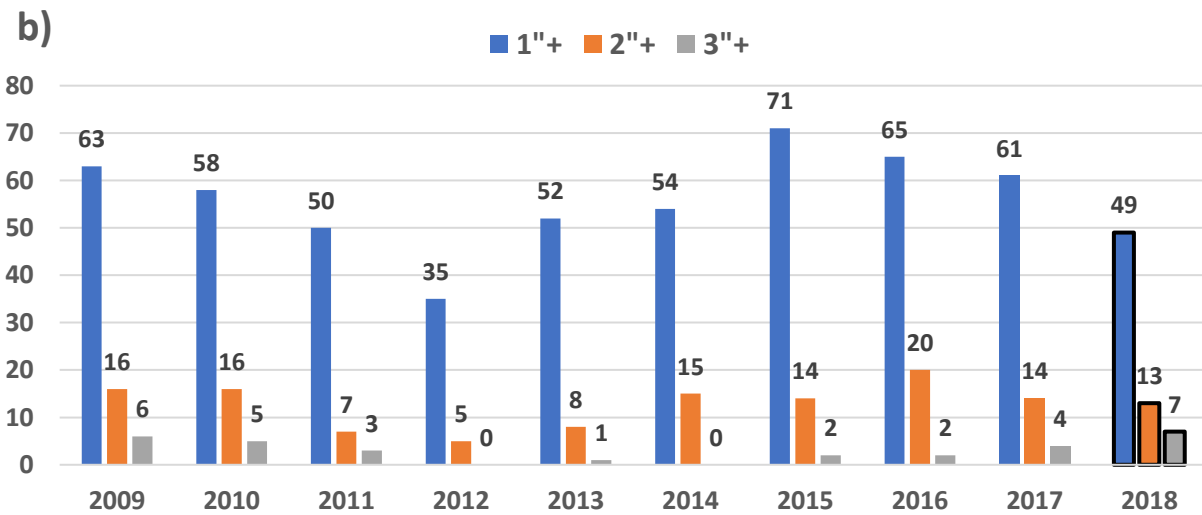
20-Year Averages: 48 (1"+), 11 (2"+), 2 (3"+)

Fig. 3.2: Time series of Colorado annual severe hail (a) reports and (b) days by size threshold for the period 2009–2018, with 2018 totals in bold bars.

76.2-mm+ hailstones, which is the most of this magnitude in state history, besting the 2010 total of nine. When tracking the proportion of all severe hailstones reported at these larger

sizes over time (Fig. 2.9a), a recent uptick is noted, culminating in 20% of all severe hail reported as 50.8 mm or greater and 3% reported as 76.2 mm or greater in 2018, both of which are the highest such percentages in the state data record. While the long-term averages of these statistics are not statistically significant, it is interesting to note the heightened contribution of larger hail reports to total severe reports since 2013. There is no *a priori* reason to expect that people across eastern Colorado are reporting more higher-end severe hailstones at the expense of lower-end (yet still severe) hailstones over time, so these record-high proportions of 50.8-mm+ and 76.2-mm+ hail is certainly a noteworthy finding. This result, albeit over a relatively short time period, is consistent with a projected increase in the proportion of larger hailstone sizes reaching the surface at the expense of smaller hailstones across the Great Plains region due to melting in a warmer climate (Mahoney et al. 2012, Brimelow et al. 2017).

A similar story exists for Colorado severe hail days in 2018. While the number of 50.8-mm+ hail days was not a new record, the number of 76.2-mm+ hail days (7) did break a state record set in 2010 (Fig. 3.2b). Twenty-seven percent of severe hail days included at least one 50.8-mm+ hailstone in 2018, and 14% of days included at least one 76.2-mm+ report (Fig. 2.9b), which is also a new state record, smashing the previous high of 9% in 2010. To summarize, it can be said that 2018 was not necessarily a year with more frequent hailstorms, but rather it was a year with more frequent *significant* hailstorms, and one in which *significant* hailstones contributed more to the total severe hail reports and days than ever before. It is worth noting that a similar story existed on the national scale in 2018. Some 10.4% of all 2018 U.S. severe hail reports were 50.8 mm+ and 1.3% were 76.2 mm+, which are among the highest percentages in this century (Childs 2018).

2. Case studies

Figure 3.3 shows a plot of all sixty-six 50.8-mm+ hail reports across Colorado in 2018, plotted according to size. A clustering of reports along the Interstate 25 corridor is present, consistent with the population bias in reporting, although a smattering of reports was also evident throughout the eastern Plains. No significant hail was reported west of 105.48°W longitude. A few of these significant hail events from 2018 were quite unique and warrant further elaboration.
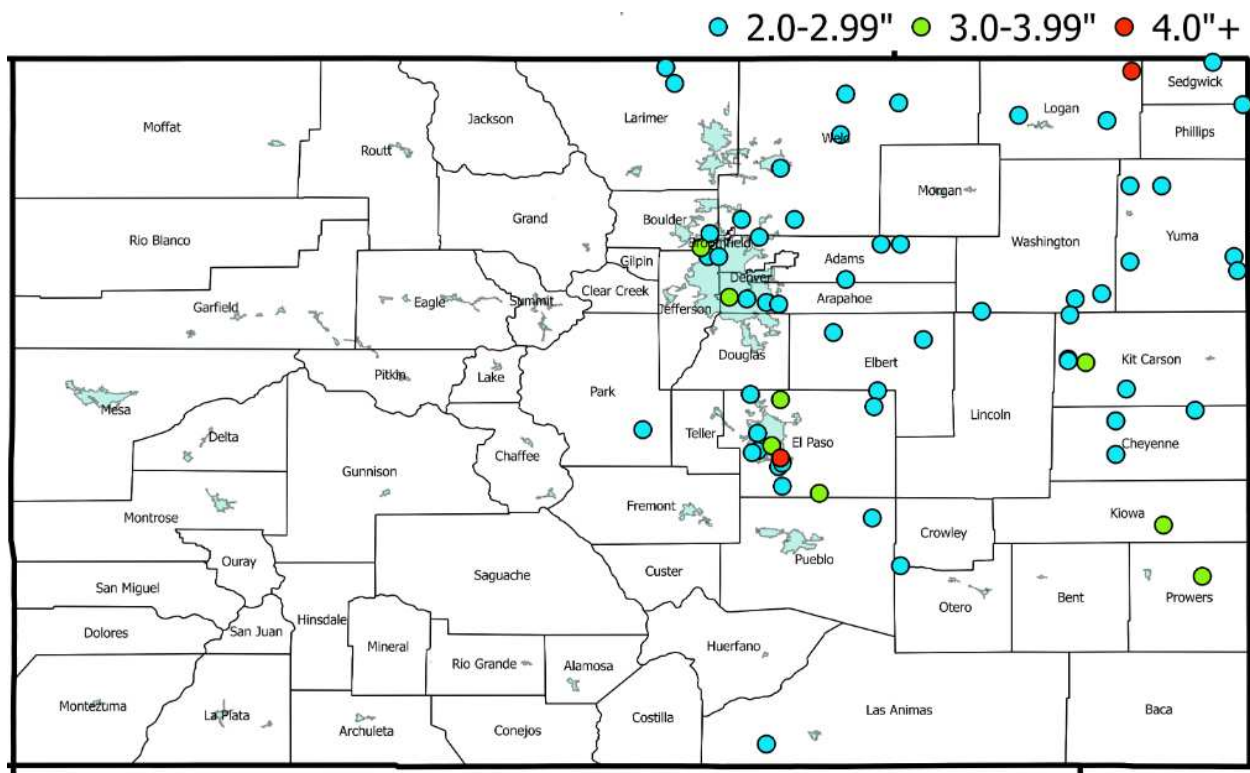
Fig. 3.3: All 50.8-mm+ severe hail reports in Colorado during 2018, plotted according to size.

(i) JUNE 13 OVERNIGHT COLORADO SPRINGS EVENT

Unlike eastern parts of the U.S., which are often plagued by overnight squall lines during the warm season, the state of Colorado sees very few severe thunderstorm events during the overnight hours. However, a significant mid-June hail event confirmed that a risk does exist from damaging hailstorms at night in Colorado. As daylight faded on 12 June 2018 over the Colorado Springs area, no signs of severe weather were imminent, and in fact the SPC convective outlook showed only a marginal risk for severe hail abutting the Colorado Springs area from the southeast. However, as the calendar switched to June 13, an outflow boundary from earlier convection in southwest Colorado ascended over the terrain adjacent to Colorado Springs. Aided by anomalously warm and moist surface conditions, a storm initiated and rapidly intensified west of town, then split into two supercells and produced a barrage of hailstones. Fig. 3.4a,b shows two radar images, thirty minutes apart, as the storm split was occurring. Eight reports of 50.8-mm+ and two reports of 76.2-mm+ hail were originally documented, which when filtered in the SPC data record validated as three 50.8-mm+ and one 76.2-mm+ hail reports (Fig. 3.4a,b). As reported by the local NWS office in Pueblo (NWS Pueblo 2018b), the right-moving supercell was responsible for the majority of the severe hail reports, while the left-moving supercell, which strangely rotated cyclonically, remained weaker. The fact that such large hail was recorded for an overnight storm is not trivial, given that most people would have been sleeping and not able to measure hailstone diameter quickly. Nevertheless, the 76.2-mm+ report(s) is only the third time in state history that hail in excess of this magnitude has been reported between the local hours of 12 AM and 9 AM, and the first time since 1982. It has been shown that nighttime severe weather, specifically tornadoes, enhances societal

risk, since people are more likely to be asleep and miss critical warning messages (Paul et al. 2003). Although overnight hailstorms have not been as fully studied, one can imagine similar societal risks. Nevertheless, overnight hailstorms in Colorado are very rare, and
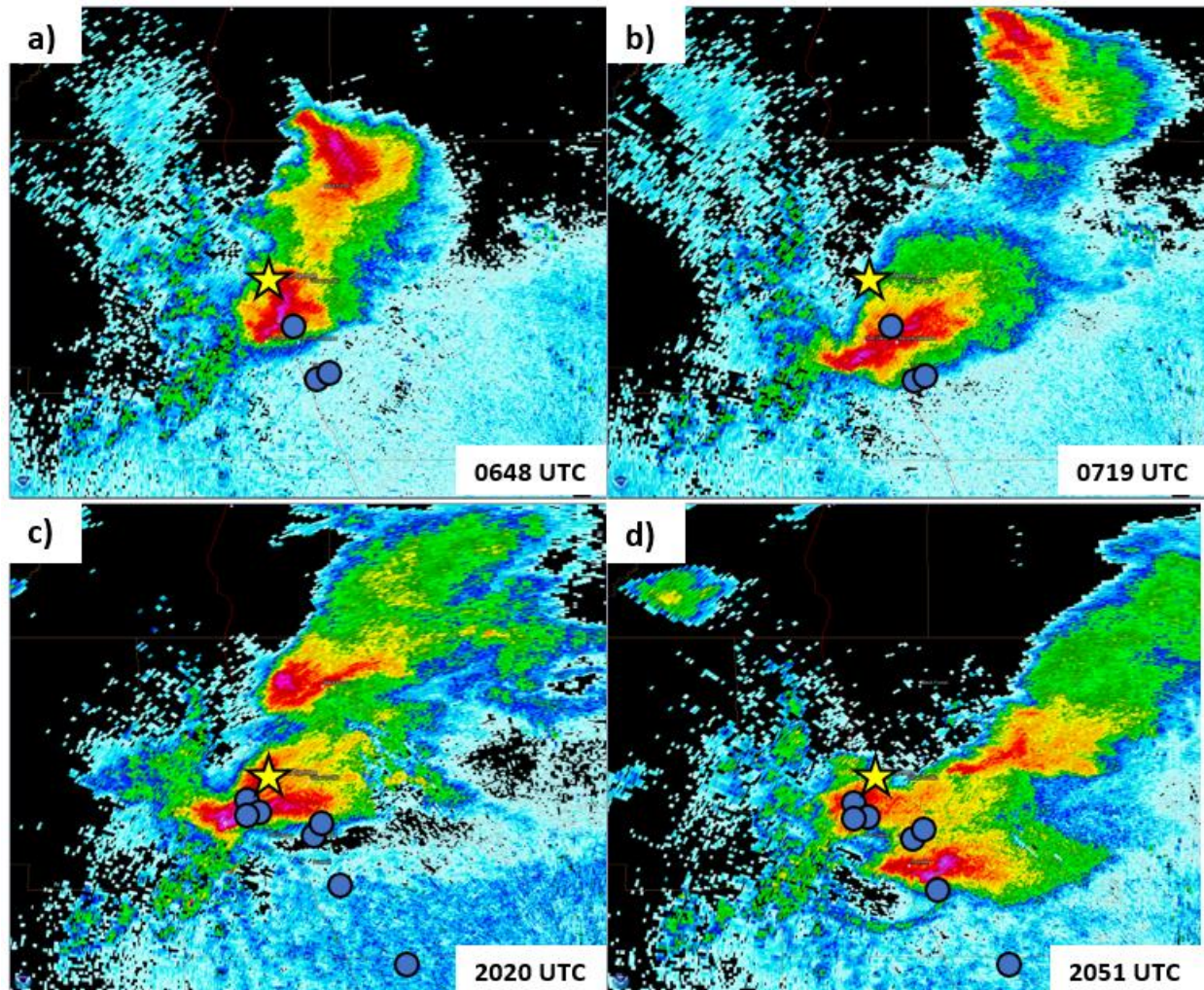
Fig. 3.4: Radar images from KPUX of the 13 June 2018 overnight hail event (a,b) and the 6 August 2018 hail Cheyenne Mountain Zoo hailstorm (c,d). Two consecutive times are shown for each event to give a sense of the system evolution. Each panel encompasses the same domain, centered on Colorado Springs (denoted by the yellow star in each panel). The blue dots denote approximate locations of 50.8-mm+ hail reports for each event. Radar data is taken from the NOAA Weather and Climate Toolkit.

while thankfully no human injuries were reported in this event, many people did awake to roof and car damage (NWS Pueblo 2018b). If nothing else, this event served as an initial pulse to what would become a dangerous hail season in the weeks and months ahead for Coloradoans. In fact, during this same week of 12-19 June 2018, a total of twenty-four 50.8-mm+ hailstones and four 76.2-mm+ hailstones were reported (including the June 13 event), which is second-highest seven-day total of both size thresholds in the modern Colorado record. This week also included a 2.75-in (69.9-mm) hailstone reported near Eleven Mile Canyon in Park County, at an elevation of around 8500 feet. Hailstones of this size at such high elevations are quite rare, as this was only the third hailstone of at least 69.9 mm to be reported in the mountainous terrain west of 105.45°W longitude.

(ii) JULY 29 HAIL OUTBREAK

While the early part of July was fairly quiet in terms of significant hail across Colorado, things began to change toward the end of the month. In particular, the afternoon of 29 July 2018 saw a series of supercells which traversed southeastward across the northeastern part of the state. Figure 3.5 shows a progression of radar images from this day, spaced two hours apart, showing the supercells responsible for the severe hail. Of the thirty-two severe hail reports on this day, seventeen were significant, which tied the state record for the most daily 50.8-mm reports set in 2012. The July 29 event was also long-lasting, with the first supercells dropping out of Wyoming in the mid-afternoon and the first Colorado severe hail report documented around 1530 MST. The final hail report of the day, a 50.8-mm report in Otero County, came in at 2230 MST, ending a 7-hour period in which at least one severe hail report was made each hour. Even more impressive, six of those seven hours contained at least one 50.8-mm+ hail report. In addition to the severe
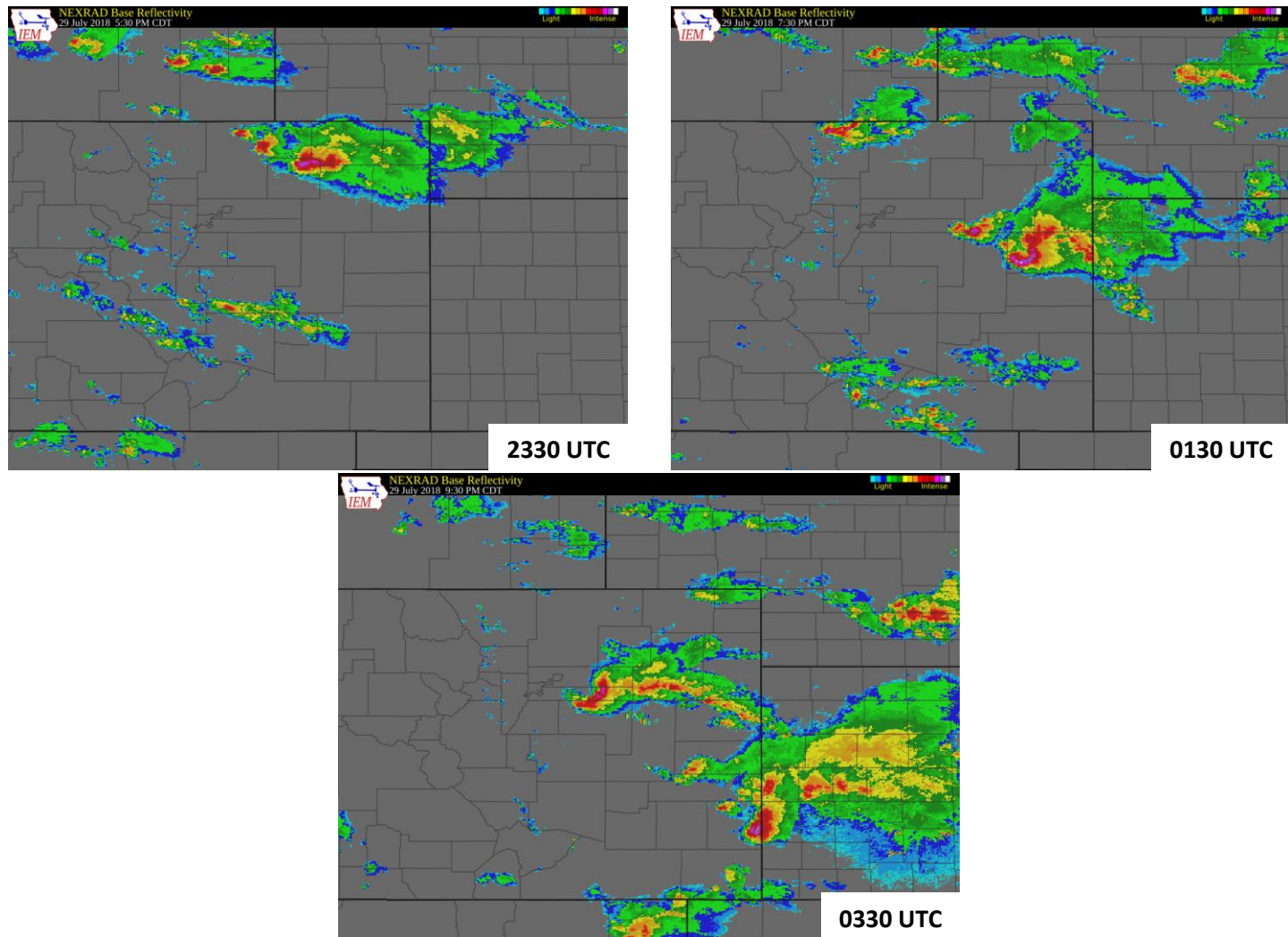
Fig. 3.5: Radar images of the 29 July 2018 hailstorms at three sequential times, taken from the Iowa State NEXRAD Radar archives. The two main supercell complexes that tracked from northwest to southeast were responsible for seventeen 50.8-mm+ hail reports across the domain.

hail, several of the supercell storms on this day produced significant straight-line winds in excess of 75 mph (NWS Goodland 2018). Numerous reports of damage to trees, crops, cars, and building windows were made as a result of the large hail and strong winds. Although no human injuries were reported due to hail, one injury was reported from strong winds when a semi overturned on Interstate 70 (NWS Goodland 2018).

(iii) AUGUST 6 CHEYENNE MOUNTAIN ZOO TRAGEDY

By far the event that garnered the most public and media attention in Colorado in 2018 was the 6 August hailstorm that wreaked havoc at the Cheyenne Mountain Zoo in southwest Colorado Springs. The SPC had a Slight Risk area for severe hail denoted on their 12Z morning convective outlook for the Colorado Springs area and points east, and especially after two significant hail events had already pummeled the area earlier in the season, this risk was not to be taken lightly. However, the hailstorm of interest on this day took a path over a more touristy part of the city, where attractions such as the Cheyenne Mountain Zoo, The Broadmoor Resort, and Seven Falls are located. Thus, families visiting from out of town may not have been aware of the severe weather risk on that day, and, despite warnings from the NWS well in advance of severe hail reports (NWS Pueblo 2018a) and alerts from various zoo staff, they may not have been adequately prepared or convinced of the destructive nature of the imminent storm. What began as a small thunderstorm that formed off the terrain west of Colorado Springs quickly grew into a supercell as it entered the populated area. Fig. 3.4c,d shows radar images of the supercell in question, spaced thirty minutes apart, with significant hail reports overlain. Very large hail up to the size of softballs fell on the zoo property, sending man and beast alike running for cover. Unfortunately, in what is a seldom occurrence in severe hail events, in Colorado

and elsewhere, over a dozen people had to be transported to a local hospital for injuries sustained from the storm. While no humans were killed, the very large hail was responsible for five zoo animal fatalities: three perished on the day of the storm, and two others died in the days following from their injuries. In addition, hundreds of cars were rendered undriveable in the zoo parking lot after having been pelted by giant hail. The zoo was closed for a week after the event to recover, repair buildings, and remove the damaged vehicles (The Denver Post 2018a). While the largest hailstone on this day was reported at 4.0 in (101.6 mm), an unofficial report of 4.5 in (114.3 mm) was gleaned from social media, which at the time tied the state record for the largest hailstone.

The August 6 event marked the third day of 2018 in which at least one 76.2-mm+ hailstone was reported in the Colorado Springs area (e.g., note the proximity of the hail events shown in Fig. 3.4a,b and Fig. 3.4c,d, which are plotted in an identical domain). This gives further evidence that the very large hail reported in this area was not an artifact, as three separate days produced hailstones that exceeded the 76.2-mm threshold. In fact, the four 76.2-mm+ hail reports over these three days in El Paso County in 2018, in which Colorado Springs is the county seat, is the highest number of 76.2-mm+ reports the county has ever seen in one year. As mentioned, El Paso County has seen the highest positive trend in annual severe hail reports of any Colorado county, while at the same time experiencing a slight decrease in annual severe hail days since 1997. While not an annual record, the 2018 total of sixty-two severe hail reports in El Paso County lies almost directly on top of the 21-year trend line (not shown), affirming a continued rise in severe hail reports in the county. Moreover, the nineteen severe hail days in 2018 for El Paso County is the highest seen in the past 10 years.

D. Attribution

With these significant hail events (and several others) across Colorado in 2018 comes the question of whether any particular synoptic pattern was prevalent during the summer months or whether individual mesoscale disturbances helped force the hailstorms. The short answer is 'Yes' and 'Yes'. From a large-scale perspective, the summer of 2018 was characterized by a persistent ridge over the western U.S. and eastern Pacific Ocean with a trough over the central and eastern U.S. (NOAA 2018). Figure 3.6a shows the composite 500-mb geopotential heights and winds for July 2018, and Fig. 3.6b shows the 500-mb height anomalies for the last two weeks of July, taken from NCEI's July 2018 Synoptic Discussion. An anomalous ridge over the West and trough in the East are clearly seen, with eastern Colorado entrenched in the strong jet region between the two anomalies. This pattern helped to drive strong mid-level northwesterly flow into the area. On the other hand, low-level flow into Colorado during the summer months is often from the south and southeast, as the low-level jet helps to advect moisture from the Gulf of Mexico northward. This scenario of low-level southeasterly flow and mid-level northwesterly flow results in strong directional wind shear, which surely played a role in promoting supercells capable of producing significant hail. In addition, the state of Colorado taps into the Southwest Monsoon during the summer. Climatologically, the Front Range urban corridor experiences its highest monthly mean precipitable water during July and August, and a secondary peak in monthly mean precipitation (primary peak is in May) is also noted during these months (Sawyer and Reichelderfer 1949, Colorado Climate Center 2017). Finally, surface temperatures were above average across eastern Colorado during the summer of 2018, and in fact the Water Year 2018 (October 2017 – September
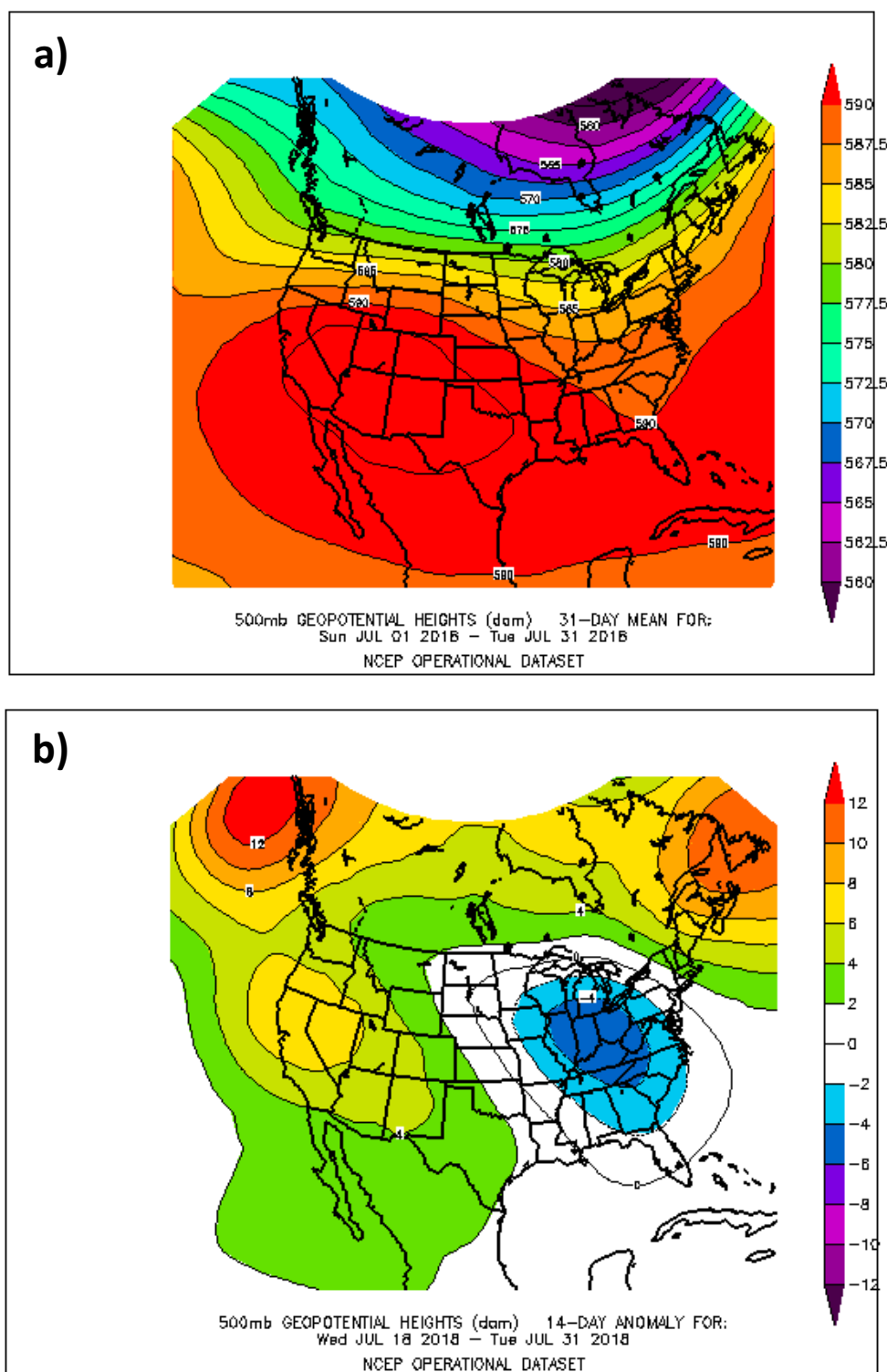
Fig. 3.6: (a) 500-mb geopotential heights July 2018 mean, and (b) 500-mb geopotential height 14-day anomaly for late July, courtesy of NCEI Synoptic Discussion.

2018) was the warmest in state history (Colorado Climate Center 2018). With this combination of anomalously warm air, monsoonal moisture, and a strong mid-level jet stream, the key large-scale ingredients for hailstorms in eastern Colorado were in place throughout the summer months of 2018.

The mesoscale conditions that existed in Summer 2018 can also be assessed through use of the North American Regional Reanalysis (NARR) data set. Specifically, anomalies of surface-based CAPE (SBCAPE), 0-6-km bulk wind difference (BWD), and the Supercell Composite Parameter (SCP) – an index computed from the product of effective storm-relative helicity, most unstable CAPE, and effective bulk wind difference – are computed for July and August 2018. The monthly averages are computed using the reanalysis times of 0Z, 3Z, 18Z, and 21Z, which represent the times of day in which the atmosphere is being primed for and then producing severe weather. The 2018 averages are compared to a climatology of monthly-averaged values for the period 2000–2017. Results are presented in Fig. 3.7 over the Colorado region. SBCAPE was higher than usual over southeastern Colorado, especially in July 2018 (Fig. 3.7a); however, this area tallied relatively few severe hail reports compared to locations further north and west, where SBCAPE was either similar or lower than climatology in July and August 2018 (Fig. 3.7a,b). In contrast, 0-6-km BWD (Fig. 3.7c,d) and SCP (Fig. 3.7e,f) were anomalously higher over all of eastern Colorado in both months, save for SCP in extreme northeastern Colorado in August. For example, monthly-averaged 0-6-km BWD anomalies of 2-4 m s^{-1} were the rule over much of eastern Colorado, and a northwest-to-southeast pattern in the anomalies can also be inferred from the plots (Fig. 3.7c,d). Indeed, the majority of severe thunderstorms that afflicted eastern Colorado in Summer 2018 traveled in this direction. In addition to
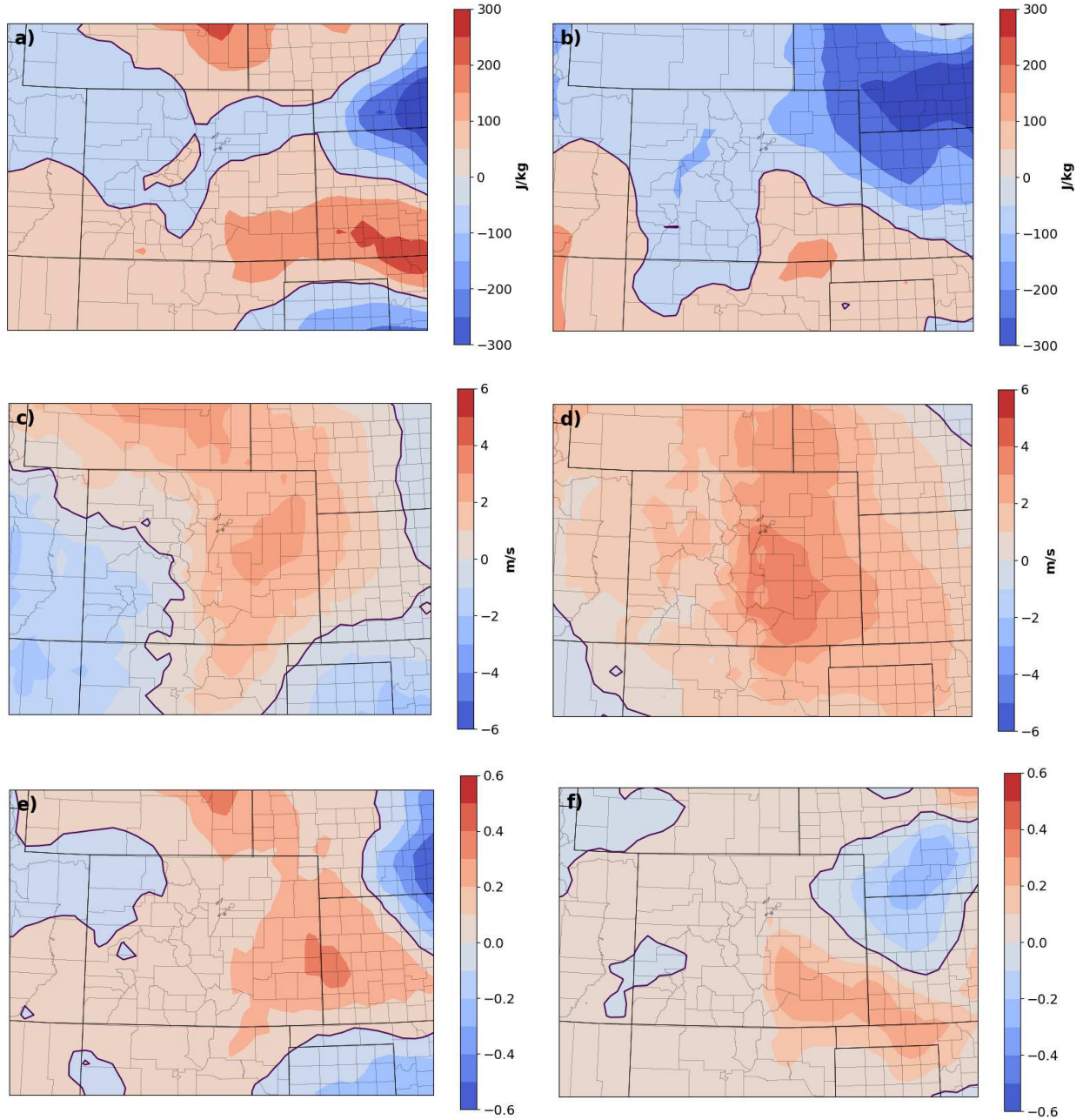
Fig. 3.7: Anomalies of monthly-averaged surface-based CAPE (a,b), 0-6-km bulk wind difference (c,d), and Supercell Composite Parameter (e,f) for July (a,c,e) and August (b,d,f) 2018, taken from the North American Regional Reanalysis (NARR). Monthly averages are computed using data from 00Z, 03Z, 18Z, and 21Z for each day of the month, and 2018 values are compared to a climatology created from the years 2000–2017.

winds that were anomalously stronger with height, wind shear also had a strong

directional component with many of the hail-producing supercells in 2018. For example, in

their report of the August 6 Cheyenne Mountain Zoo hailstorm, NWS Pueblo (2018a) note

the presence of a high-pressure system centered over the Four Corners region and low-

level southeasterly flow which helped to advect warm and moist air from the Gulf of Mexico

northwestward into Colorado. These low-level southeasterlies, in addition to opposing the

strong upper-level northwesterly flow not usually present during a monsoonal

thunderstorm setup, thereby promoting strong vertical directional shear, were also driven

upslope against the terrain, contributing a source of lift to help trigger convection. This

setup, namely high pressure near the Four Corners region and low-level southeasterly flow,

was in fact a common feature on many days with significant hailstorms in 2018.

Another way to analyze the convective parameter anomalies from NARR is by

computing how many times a parameter exceeded a respective threshold in July and

August 2018 versus the average number of times it did so in the climatology. As such,

Table 3.3 presents the number of threshold exceedances of SBCAPE (> 2000, > 2500, and >

3000 J kg^{-1}), 0-6-km BWD (> 20, > 30, and > 35 m s^{-1}), SCP (> 2, > 3, > 4), and the

combinations of SBCAPE > 2000 J kg^{-1} with 0-6-km BWD > 20 m s^{-1} and 0-6-km BWD > 30

m s^{-1}. If at least one grid point across the eastern Colorado domain (37-41°N, 102-

105.3°W) exceeded the respective threshold at a particular reanalysis time (0Z, 3Z, 18Z,

21Z for each day in July and August), that particular time was assigned a value of '1'. The

domain exceedances were then summed to get totals for July, August, and both months

combined, and for the climatology of 2000–2017, the totals were averaged over the 18-year

period. Thus, the maximum possible number of total threshold exceedances for the two

months is (4 times per day * 31 days in July) + (4 times per day * 30 days in August) = 244.

Table 3.3 shows that all thresholds for SBCAPE over eastern Colorado were exceeded fewer

times in 2018 than the climatological average, affirming that anomalously high instability

was not a major factor leading to the damaging hailstorms seen. The threshold exceedance

Table 3.3: Number of reanalysis times (0Z, 3Z, 18Z, and 21Z) in the months of July and August in which at least one grid point in the eastern Colorado domain exceeded the specified threshold of surface-based CAPE (SBCAPE), 0-6-km bulk wind difference (BWD), Supercell Composite Parameter (SCP), and the combination of SBCAPE and 0-6-km BWD. The year 2018 is compared to a climatology consisting of the July and August averages over the period 2000–2017.

	2000-2017 Average			2018			Difference
	JUL	AUG	SUM	JUL	AUG	SUM	
SBCAPE >3000	4	2	6	4	1	5	-1
SBCAPE >2500	10	6	16	7	4	11	-5
SBCAPE >2000	24	16	40	26	12	38	-2
0-6-km BWD >35	0	2	2	3	2	5	+3
0-6-km BWD >30	5	6	11	21	4	25	+14
0-6-km BWD >20	49	50	99	39	47	86	-13
SCP >4	8	6	14	10	8	18	+4
SCP >3	13	9	22	15	11	26	+4
SCP >2	25	17	42	39	22	61	+19
SBCAPE >2000 + 0-6-km BWD >30	1	0	1	0	1	1	0
SBCAPE >2000 + 0-6-km BWD >20	7	4	11	5	5	10	-1

counts for the combinations of SBCAPE and 0-6-km BWD were also near average in 2018.

On the other hand, there were many more instances of high (i.e. > 30 m s^{-1}) 0-6-km BWD in

July and August 2018 than the 2000–2017 average. In particular, sixteen more reanalysis

times in which 0-6-km BWD exceeded 30 m s^{-1} occurred in July 2018 than the July

climatological average. Similarly, all SCP thresholds were exceeded more frequently in

2018 than the 2000–2017 average, with nineteen more exceedances of SCP > 2. Again, it

was not that more frequent occurrences of high CAPE led to the greater number and proportion of significant hail reports across eastern Colorado in 2018; rather, anomalously high vertical shear combined with sufficient CAPE and a strong moisture transport from the Gulf supported such a favorable severe weather environment.

In the wake of eastern Colorado's bizarre and devastating hail season, one may be inclined to ask whether or not climate change was responsible. Climate change attribution is still in its infancy, and determining whether a single event was the result of changing climate is difficult and potentially misleading. In the case of severe hail events in Colorado in 2018, other factors beyond climate change are most certainly at play, not the least of which is the population bias in reporting. Some of the large hail reports are surely the result of having a large number of people in the areas where hail fell. Still, the similar number of 76.2-mm+ hail days (7) and hail reports (10), for example, does affirm that the very large-hail-producing storms were more frequent in 2018. From a meteorological perspective, recent research does support an increase in environments favorable for severe weather (and specifically large hail) in the future. Brimelow et al. (2017) showed a tendency toward more frequent occurrence of significant hailstones (i.e. > 4 cm) in the future, along with an increase in mean hail size. However, their results are dependent upon region, with the Great Plains region (including eastern Colorado) having the greatest signal toward future increases. The Southeast, on the other hand, was found to experience a decrease in large hail over time as temperature and moisture increases in the already-sultry region lead to higher melting rates that overcome any hail growth from increased buoyancy. Indeed, a changing freezing level height as the atmosphere warms may have an important impact on future hail size distributions, as smaller hail becomes more likely to

melt before reaching the surface (Xie et al. 2010, Mahoney et al. 2012, Dessens et al. 2015). High-resolution convection-allowing simulations have become popular in recent years to assess how certain storms or patterns may look in a future climate. Towards this end, Rasmussen et al. (2017) used a pseudo-global warming approach and found an increase in the number of "intense" thunderstorms (defined by them as convective storms with maximum composite reflectivity > ~40 dBZ). They attribute this increase in strong convection to increased CAPE and also increased CIN in the future; when the enhanced CIN is overcome, more vigorous convection ensues. While their study did not assess individual hazards, simple hail growth dynamics would favor larger hailstones with stronger storms, as stronger updrafts are able to loft the growing hailstone further into the upper ice regions of a cloud. These topics are explored further in Chapter 4.

E. Conclusions and Application

The 2018 hail season in Colorado served as a reminder of the destruction that large hail can bring to people, animals, and property. The state of Colorado is by no means immune to significant hail events, having seen several multi-million-dollar hail disasters in this century and at least one in 2018 (RMIAA 2018). However, the record number of significant hail reports and days in 2018 does present the continuation of a concerning trend toward more extreme hailstorms in Colorado and a consequent increasing potential to cause serious damage and injury. Favorable meteorological conditions, such as anomalously strong upper-level northwesterly flow, the persistent synoptic ridge-trough pattern, and low-level moisture advection, were partly responsible for the damaging hailstorms in 2018, but so too were the population and infrastructure components. As more people continue to move into the Front Range urban corridor, there is a call for action

among professionals and the public alike. The Cheyenne Mountain Zoo incident of 6 August

2018 proved that warning procedures at tourist attractions need to be assessed for

potential improvements and practiced regularly. With the infamous Denver hailstorm in

May 2017 and now the 6 August 2018 event should come a serious discussion about

implementing covered parking in large lots found at car dealerships, tourist attractions,

and airports. Such an endeavor would be costly, but could save major headaches in the

long run if the trend towards more frequent significant hail events continues through the

21st century. The significant hailstones that were reported in the foothills and

mountainous terrain in 2018 should also be a reminder to hikers and outdoor enthusiasts

to keep an eye to the sky and finish hikes before midday, not just due to the lightning

hazard but also due to hail potential from high-elevation convective storms. Societal

awareness must also increase following the 2018 hail season to improve the understanding

of the general public in terms of both the science behind hailstorm projections and also the

practical steps that one can take to mitigate the negative impacts from hailstorms.

Effective risk communication is of great importance in garnering public attention to the

hazard and can potentially lead to greater rates of taking appropriate action steps (Mileti

and O'Brien 1992, Trumbo 2013, Morss et al. 2017), and Chapter 5 will explore this aspect

from an agricultural perspective. While many residents of Colorado were left with a major

roof repair or other property damage following the 2018 hailstorms, a greater public

awareness of current and future expectations of the local hail landscape, combined with

action steps taken by decision-makers, can ultimately serve to offer a greater protection to

life and property across the Front Range and eastern Plains of Colorado in upcoming hail

seasons.

CHAPTER 4: PROJECTING END-OF-CENTURY HUMAN EXPOSURE AND TO TORNADOES AND SEVERE HAILSTORMS IN EASTERN COLORADO: METEOROLOGICAL AND POPULATION PERSPECTIVES[4]

Having established an updated climatology of tornadoes and severe hail across eastern Colorado, we now arrive at the question of how changes in the frequency and spatial distribution of these hazards, as well as changes in population, intersect to alter the number of people potentially exposed to tornadoes and hailstorms by the end of the 21st century. Specifically, I ask "How many people in eastern Colorado will be in harm's way of tornadoes and hailstorms in the future compared to the present day, and how do the respective projected changes in meteorology and population contribute to the changing exposure?" This chapter will begin by describing the datasets and methods used to model and project changes in convective hazards and population, followed by presenting a suite of meteorological and population changes across the eastern Colorado domain by the year 2100. These changes are then combined in a Monte Carlo statistical framework to assess a range of potential changes in human exposure.

A. Background and Definitions

Even with laudable advancements in forecasting skill and warning messaging for tornadoes and severe hailstorms, significant damage and, in some cases, injuries and fatalities, still occur (Ashley 2007, Ashley and Strader 2016, Martius et al. 2018, Prein and Holland 2018, Sobel and Tippett 2018). The extent to which severe weather hazards will

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[4] Adapted from Childs et al. (2020c, *WCAS*)

change in frequency and location in the future owing to climate change is an ongoing

research question (Trapp et al. 2007, Brooks 2013, Diffenbaugh et al. 2013, Gensini and

Mote 2015, Tippett et al. 2015, Hoogewind et al. 2017). Assessment of future human risk

from these hazards must not only consider meteorological variables that prime the

atmosphere for severe weather, but also the numerous socioeconomic factors which affect

the public's ability to receive and respond to warning messages, as well as cope with the

impacts (Changnon et al. 2000, Pielke 2005, Bouwer 2011, Ashley et al. 2014, Visser et al.

2014, Strader et al. 2017). These societal factors also influence the evolution of population

and development patterns and thus the number of people exposed to tornadoes and severe

hailstorms.

Within natural hazards literature, there are multiple definitions and meanings for

many of the terms used herein (Paul 2011). This work elects to follow the framework of

the Intergovernmental Panel on Climate Change (IPCC) SREX report, which defines overall

hazard *risk* as the interaction between hazardous weather and *impacts*, the potential

negative effects consequent from the hazard (NRC 2009, IPCC 2012). Three elements

contribute to risk, including *exposure*, which, as the main focus of this study, is defined as

the number of persons potentially affected by tornadoes or severe hailstorms (Strader et al.

2017). *Vulnerability* is defined as the susceptibility of a person or system to experience

harm from a hazard, and often includes the constructs of *sensitivity* and *adaptive capacity*

(Cutter et al. 2000, Morss et al. 2011). The third element is simply the *hazard* itself, which

is contextualized as the climatological probability of a tornado or hailstorm occurring in

space and time (Morss et al. 2011, IPCC 2012).

Many prior studies have examined human exposure to severe weather hazards. For example, Bouwer (2013) found that flash flood and hurricane losses due to human exposure outweigh losses due to anthropogenic climate change out to the year 2040. Losses due to hailstorms are increasing globally in large part due to the expansion of the built environment (Changnon 2009, Prein and Holland 2018, Bouwer 2019). Similarly, Ashley et al. (2014) coined the 'expanding bull's-eye effect', which describes how population growth and the expansion of the built environment or urban sprawl has led to increased hazard impact frequency and magnitude on society. This effect has been linked to an increased tornado disaster potential in the Chicago metropolitan area (Ashley et al. 2014) and five other U.S. cities (Rosencrants and Ashley 2015). In addition, Strader et al. (2017) projected a three-fold increase in tornado disaster potential by 2100 from a combined increase in tornado occurrence and the built environment (i.e., housing units) footprint. This research builds upon previous work in several ways. For one, severe hail is considered in addition to tornadoes, which represents a hazard that has shown increasing potential for loss, and, in some regions such as eastern Colorado, an increase in number of reports, days, and hailstone diameter, in recent decades (Allen et al. 2015a, Childs and Schumacher 2019, Trapp et al. 2019). A more realistic spatial representation of human exposure is considered through high-resolution Shared Socioeconomic Pathway (SSP) population scenarios as well as projected frequency and spatial distributions of tornadoes and severe hail using high-resolution dynamically-downscaled climate model output for control and future climate scenarios. Moreover, the small domain of eastern Colorado (37°-41°N, 102°-105.3°W; Fig. 1.7) offers an excellent example of the cumulative effects

that meteorology and population can have on a local scale that may not be gleaned from studying a broader area (see Chapter 1).

While this research is focused on eastern Colorado, the methods presented herein may be applied to other localized regions of the country, if desired. Assessing natural hazard risk and societal vulnerability across a larger spatial domain is certainly helpful in providing large-scale patterns and allowing for influences such as climate change to be considered more appropriately, but localized analyses such as those conducted in this study appeal to the "me-factor" that points to the desire for an individual to know exactly what is going to happen to him or her in a hazard event (Nagele and Trainor 2012, Morss et al. 2016, Childs and Schumacher 2018a). This is especially true in a region such as eastern Colorado, where both vibrant crop and ranching communities and the adjacent, rapidly-developing metropolitan area experience damaging severe weather events.

B. Tornado and Hail Monte Carlo Models

Monte Carlo (MC) statistical approaches draw upon random numbers and probability to repeatedly sample and run statistics on a population to give estimated solutions (Mooney 1997). MC methods have been applied to a variety of problems in the atmospheric sciences, from reflectivity of clouds (Barker et al. 2003), to precipitation impacts on aerosols (Zhao and Zheng 2006), and uncertainty estimates of disaster costs (Smith and Matthews 2015). To explore the impacts of population and tornado statistics on the human and the built environment, the Tornado Monte Carlo (TorMC) model was developed by and described at length in Strader et al. (2016). TorMC has proven utility in projecting future changes in tornado exposure over large areas the country. For example,

both Strader et al. (2016) and Strader et al. (2017) illustrate that physical exposure, as measured by housing units, outweighs frequency of tornado events in its contribution to disaster severity. This study applies TorMC to the localized eastern Colorado domain to assess the contributions of population dynamics and climatological changes to human exposure by the year 2100. In addition, a Hail Monte Carlo (HailMC) model is developed using the framework of TorMC to investigate human exposure from severe hailstorms (Fig. 4.1).
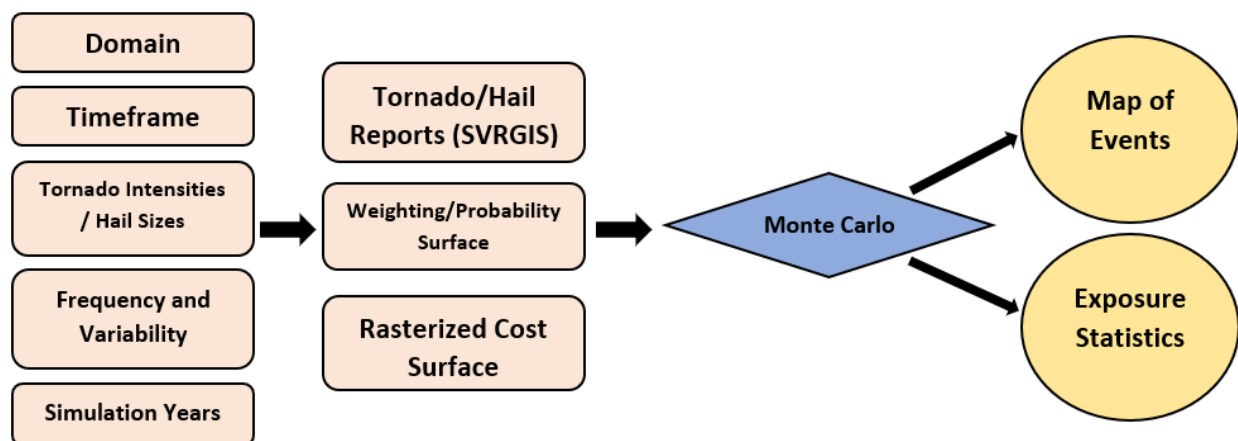
Fig. 4.1: Basic structure of TorMC and HailMC models. The far left rectangles represent basic user inputs, and the next column of rectangles shows the shapefiles and raster files that are created and input into the model. The ovals represent the output from the Monte Carlo simulations, namely a plot of tornado paths or hail swaths, as well as human exposure statistics.

TorMC and HailMC are composed of multiple user inputs followed by a simulation. The user must designate the desired magnitude range of the hazard to be simulated, in this

case the EF-scale rating for tornadoes and hailstone diameter. For the eastern Colorado domain considered, all EF-scale ratings are considered for tornadoes, as 96% of all tornado reports since 1997 have been of the (E)F0 or (E)F1 variety (Childs and Schumacher 2019). Although the U.S. (E)F0 tornado record shows a non-meteorological jump in the 1990s due to the implementation of Doppler radar (Verbout et al. 2006, Agee and Childs 2014), for the temporal and spatial domain considered here, this artifact is largely absent, as TorMC samples only those tornadoes within the eastern Colorado domain. For HailMC, the severe threshold of 25.4 mm used by the NWS is employed. While the number of significant (50.8-mm+) hail reports in eastern Colorado is increasing over time (Childs and Schumacher 2019), they account for only 6.5% of all severe hail reports in the data record, and the relative change in human exposure from HailMC was found not to be sensitive to the selection of minimum hailstone size. The range of years over which to select tornado and/or severe hail historical reports is also entered. This study uses the period 1997–2017, which represents the Doppler radar era characterized by much higher tornado and hail data reliability compared to previous years (Verbout et al. 2006, Agee and Childs 2014, Allen and Tippett 2015).

TorMC and HailMC also ingest two shapefiles: (a) the domain of interest, in this case eastern Colorado (37-41°N, 102-105.3°W), and (b) GIS files of the initial points of tornado and severe hail reports, accessed from the Storm Prediction Center's (SPC) SVRGIS. Raster surfaces must be created and input into the MC models. A control weighting surface for each hazard represents a spatial probability of tornado and severe hail occurrence based on the historical distribution of reports over the 1997–2017 control period. A future weighting surface is also created, as described in Section D, to represent the projected

future spatial distribution of these hazards across eastern Colorado. Rasterized cost surfaces of human statistics, in this case a control population surface for the year 2000 from the 1-km Gridded Population of the World (GPW) Version 3 data set and five 1-km SSP version 1.1 population projections for the year 2100, are also input into the models (available online at http://www.cgd.ucar.edu/iam/modeling/spatial-population-scenarios.html).

For each year in the 1000-yr MC simulations for both control and future statistics, tornado paths and hail swaths are created by first "grabbing" a tornado or severe hail report according to the probabilistic weighting surface. In TorMC, each selected tornado is assigned a magnitude and length (km) from the database, and a width (km) that fits a Weibull distribution according to its magnitude (Brooks 2004). A tornado azimuth, that is, its direction of travel, is selected randomly from a wider sample of all tornadoes in the CONUS for the 1997–2017 period to avoid a bias toward erroneous northerly azimuths in eastern Colorado. With these attributes, a tornado polygon geometry is created and placed onto an output data frame. HailMC proceeds similarly, with each simulated hail event assigned a diameter from eastern Colorado SPC reports. Severe hail reports are documented as occurring at a single point in space, but in reality, hail of the reported magnitude occurs in a swath surrounding the point. As such, HailMC assigns each simulated hail report a length and width of 0.1 km and an azimuth of zero, creating a square of hail. While hail often falls in longer and more irregular swaths or contains multiple sizes within the same swath, this study is concerned with *relative* changes in human exposure as opposed to absolute changes. In other words, hail swaths of equal sizes in the control and future simulations allow for a homogeneous comparison of potential

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impacts. Experiments were run using larger hail swaths, but the relative change in human impacts did not vary significantly.

Once all tornado or severe hail polygons are created, a 1-km cost surface of GPW or SSP population density is overlain using the same coordinate reference system. The number of people underneath a polygon can then be computed for each scenario of interest. Numerous options exist for how to calculate human statistics within a gridded domain, but this study elects to define an entire grid cell as being affected if a tornado path or hail swath intersects any part of it (e.g., Fig. 4 from Strader et al. 2016). In total, three simulations are run for each hazard: a control run, one with a uniform amplification of tornado and severe hail reports across the domain and the control weighting surface, and one with uniform amplification of tornado and severe hail reports and the future weighting surface. The control cost surface and each of the five SSP projections are then overlain on each simulated tornado and hail landscape to give a range of potential impacts.

C. Population Dynamics

1. Background and approaches

The extent to which local, regional, and national population landscapes change is governed by a variety of factors. The U.S. Census Bureau conducts a national census on a decadal basis, amassing a wide variety of population statistics. These reports are useful for extracting broad trends of population at relatively coarse resolution (e.g., state-level, regional, national). For finer-scale population statistics, many state demography offices can provide county-level, block-level, or even neighborhood-level data. However, even detailed procedures used by the U.S. Census Bureau must contend with many uncertainties.

For example, what exactly is a household? How should abandoned houses where people are no longer living be treated? What about people who do not respond to the census request? An even more daunting challenge is projecting population many years in advance. One can imagine a number of potential factors that could entirely change the population dynamics of a region. This is a problem that has recently attracted the attention of several research groups, and sets of population projections, each with different possible scenarios, now exist which project population out to the year 2100. The projections in use today are mostly based on national-level demographic trends, but can be downscaled to as fine a resolution as 100 meters. The population changes in these small grid boxes are thus based on national-level trends, which consequently can produce some unrealistic artifacts and patterns in the projections at the local level. However, state-level demographic influences are currently being developed and incorporated into some new sets of population projections for increased precision (B. O'Neill, personal communication).

The uses of population projections are many and appeal to different sectors of society.[5] Changes in population lead to a recategorization of land cover and land use, which is often manifested as agricultural land being converted into residential or commercial usage. This repurposing of the land affects ecological and biological systems, impacts food supply and demand, and is directly related to changes in emissions and radiation, which in turn affects the global energy balance. Air pollutants can be altered due to population change, as can the number of people exposed to vector-borne diseases and viruses. Of most relevance in this study is the impact of population changes on human risk from weather

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[5] Much of the following paragraphs are based on background information contained in Jones and O'Neill (2016) and Jones and O'Neill (2013), and references therein.

and climate hazards, specifically tornadoes and severe hailstorms. It is therefore advantageous to have some idea of how population is expected to shift in the future, so that decision- and policy-makers can prepare for and mitigate any related negative impacts.

The Intergovernmental Panel on Climate Change (IPCC) produced a Special Report on Emissions Scenarios (SRES) in the year 2000 to propose potential effects from varying degrees of greenhouse gas emissions over the coming century. Global population projections were developed out of the five SRES scenarios (A1, A2, B1, B2, Base Case) using broad assumptions about regional population change. In 2014, the Shared Socioeconomic Pathways (SSPs) were developed to show how various aspects of society may evolve over time, and this data set has subsequently gained a following in natural hazards research (Ebi et al. 2014). The five SSPs are based on national-level projections of various sectors such as economics, education, technology, and immigration, and are meant to provide a measure of how a society will be able to adapt to and mitigate the influences of changes in climate. Specifically, the five SSPs are labeled as 'Sustainability', 'Middle-of-the-Road', 'Regional Rivalry', 'Inequality', and 'Fossil-fueled Development.' Table 4.1 depicts a slightly modified table from Jones and O'Neill (2016) showing the broad demarcations of population growth and urbanization levels of the five SSP projections. Population growth is based on categories of fertility and income, including high-fertility, low-fertility-high-income, and low-fertility, for a particular country group (and, by extension, a particular region of that country). Urbanization level is modeled based on categories of income alone, and incoming migration is also accounted for. It is also important to note that the assumptions of high, medium, or low population growth and fast, central, or slow urbanization levels are not constant but are rather subjective to a particular country group, such that a high

population growth in a low-fertility country is not the same rate of growth as a high

population growth in a high-fertility country (Jones and O'Neill 2013). Many other

assumptions and complex modeling procedures are utilized to arrive at the rather simple

depiction in Table 4.1, and thus the reader is referred to the supplemental information in

Jones and O'Neill (2016) for a detailed description of the methodology and the specific

traits of each SSP.

Table 4.1: Summary of assumptions about population growth and urbanization level, and the resulting spatial pattern, for each of the five SSP scenarios, for given country statistics. Population growth levels are given according to fertility categories, where 'High' indicates countries with birth rates in excess of 2.9, 'Other Low' indicates counties with birth rates less than 2.9, and 'Rich Low' indicates countries designated as a high income country by the Word Bank with birth rates less than 2.9, for the period 2005-2010 (Samir and Lutz 2017). Urbanization level is connected to current income levels for each county or region. Reproduced from Jones and O'Neill (2016).

	SSP1 Sustainability	SSP2 Middle-of-the-Road	SSP3 Regional Rivalry	SSP4 Inequality	SSP5 Fossil-fueled Development
Fertility	***Population Growth***				
High	Low	Medium	High	High	Low
Other Low	Low	Medium	High	Medium-low	Low
Rich Low	Medium	Medium	Low	Medium-low	High
Income	***Urbanization Level***				
High	Fast	Central	Slow	Central	Fast
Medium	Fast	Central	Slow	Fast	Fast
Low	Fast	Central	Slow	Fast	Fast
	Spatial Pattern				
	Concentrated	Historical Patterns	Mixed	Mixed	Sprawl

Jones and O'Neill (2016) created a set of global spatial population projections in

decadal increments out to the year 2100 that are both qualitatively and quantitatively

consistent with the SSPs. Gao et al. (2017) describes a gravity model-based downscaling

approach to map spatial patterns and their changes over the U.S. In short, the 1/8° SSP

projections are downscaled to a 1-km grid using a 1-km population count from the Global

Urban-Rural Mapping Project (GRUMP) version 1 (CIESIN 2011), which incorporates the

finest level census data available. An aggregation procedure then maps the 1-km GRUMP

data onto 1/8° grid to match the SSP narratives. Finally, a 1-km weighting map is created

to show how the coarser population is spread among the 1-km grid cells, which is then

multiplied to the 1/8° projections. This method is followed by Jones and O'Neill (2016) to

aggregate the GPW base case population surface to match the resolution of the SSPs. Gao

(2017) cautions that "subtle spatial artifacts" exist in the 1-km population projection maps,

but these are generally found outside of North America, where population statistics are less

reliable. Nevertheless, the 1-km results were cross-validated with 1/8° resolution for the

domain of interest, and only miniscule changes were found in relative population changes

across eastern Colorado that do not affect the overall conclusions.

2. Eastern Colorado projections

The base case population used in the SSP framework is taken from the GPW 1-km data set

for the year 2000 (Fig. 4.2). The end-of-century, downscaled 1-km SSP projections are

clipped to the Colorado state boundary using GIS. Each SSP scenario evolves differently

over time according to its underlying socioeconomic assumptions (Fig. 4.3). None of the

SSP scenarios depict much population change over the eastern Plains, but distinct features

are noted along the Front Range urban corridor. For example, SSP5 produces enormous

population growth in the Front Range cities (greater than 50,000 persons in many adjacent

grid boxes) and also expands suburbs in areas north of Colorado Springs, fills in gaps

between Denver and Castle Rock to the south and Fort Collins to the north, and increases

the population along and east of Interstate 25 in northern Colorado. In this scenario, the

reliance on fossil fuels continues to spur development; income growth, innovation, and

investments in education are high; and a large number of migrants come to the U.S. for

work. As such, rapid urbanization occurs, with a spatial pattern of population extensions

around metropolitan areas (Jones and O'Neill 2016). SSP1 (Sustainability) and SSP2

(Middle-of-the-Road) scenarios are the most consistent with recent demographic trends,

with modest income growth and migration, as well as investments in education and the

environment. This results in a moderate increase in population along the Front Range

urban centers with some east-west population extension in both SSP1 and SSP2. SSP4

shows a more muted response along the urban corridor as well as areas of decreasing

population on the edges of cities. This scenario, coined "Inequality", is characterized by

slow economic growth and a lack of opportunities in rural communities, favoring a more

concentrated population in cities and industrial areas. Finally, SSP3 evolves in such a way

as to project much less population along the urban corridor by 2100. The SSP3 scenario of

"Regional Rivalry" represents economic uncertainty, security concerns, and low

technological growth, leading to lower fertility in high-income countries. This results in a

dying population, but also pockets of wealth beside slums in big cities as economic growth

is stunted. It is also interesting to note how other smaller communities such as Fort

Morgan and Sterling on the eastern Plains are projected to grow in all scenarios except

SSP3 (Fig. 4.3), whereas the town of Limon is not expected to experience much growth

under any scenario, perhaps due to its currently-small industrial sector.

To summarize, numerous factors must be considered in projecting end-of-century

population density, including immigration, education, foreign relations, technological
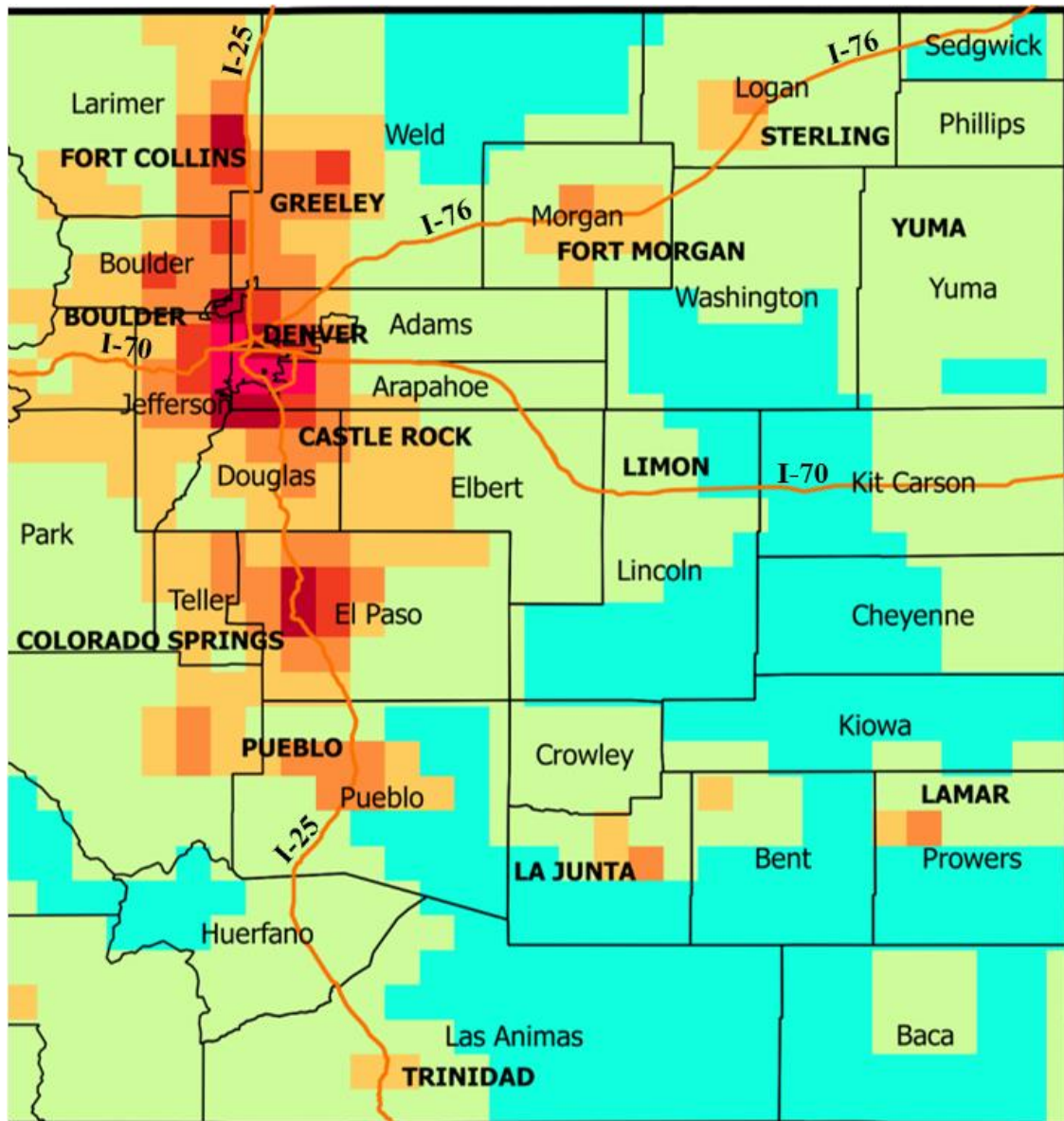
Fig. 4.2: Base case population density for the year 2000, taken from the Gridded Population of the World data set at 1/8° gridded resolution. The units shown are number of persons per 1/8° X 1/8° grid box. County names are in normal font type, select cities are bolded in all caps, and Interstate highways are marked by orange lines.
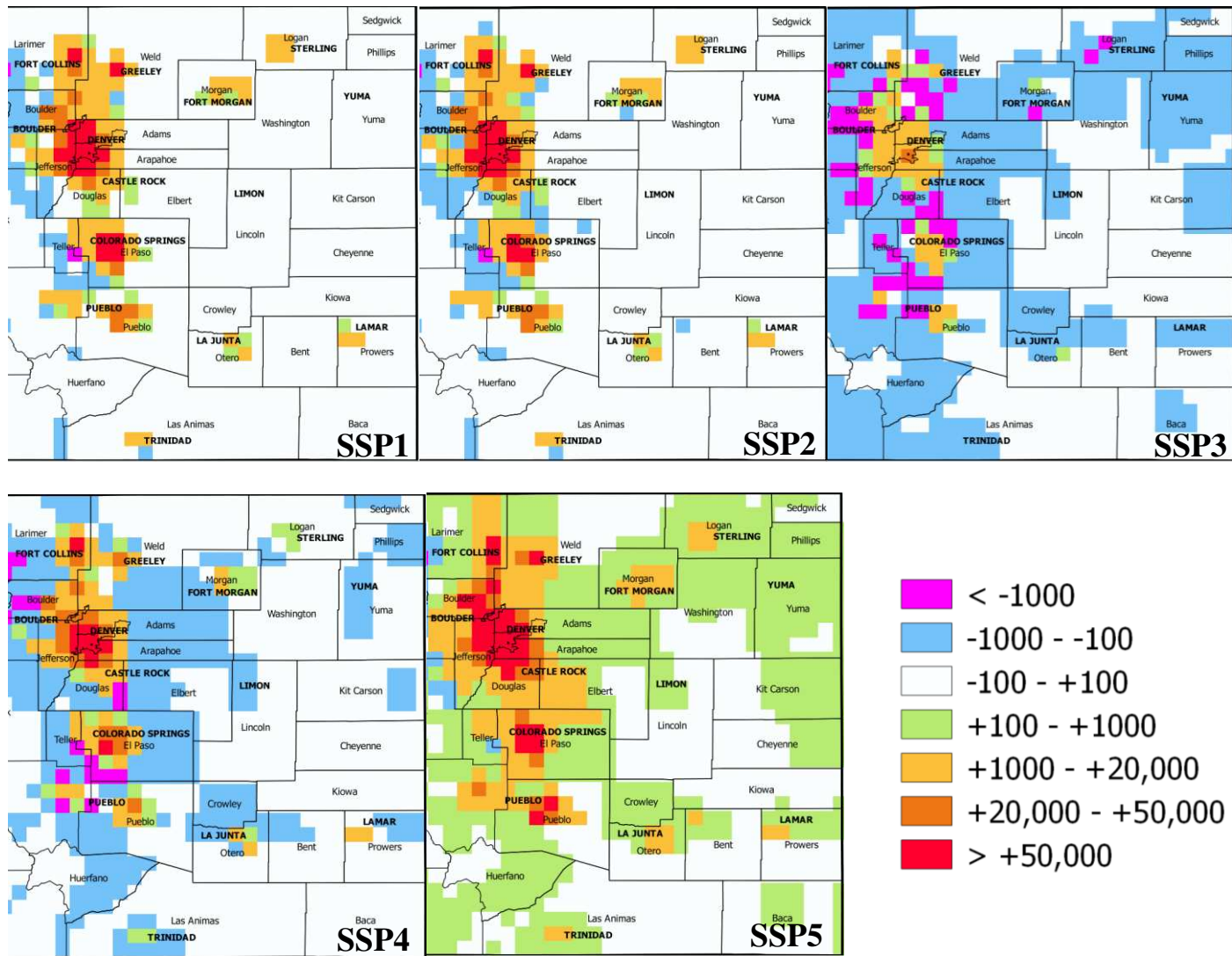
Fig. 4.3: Change in population between end-of-century SSP projections and the GPW year 2000 base case population at 1/8° resolution.

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growth, and local factors specific to Colorado that are not explicitly accounted for in data set used here (Jones and O'Neill 2016). Each of the five SSPs predict population growth over most areas relative to the GPW base case scenario, especially along the Front Range urban corridor. However, there are subtle differences in how cities are projected to expand and also in the relative growth of smaller towns on the eastern Plains. While the likelihood of a single SSP projection materializing is slim, the take-away message is that a wide range of population scenarios for eastern Colorado exists, which consequently impacts the number people who may be exposed to tornadoes and severe hail in the future.

D. Tornado and Severe Hail Projections

1. Background and approaches

Projecting changes in severe weather over a region has its own set of challenges. It is very difficult to predict whether an ongoing supercell thunderstorm will produce a tornado or severe hail, let alone try to predict when and where a tornado or hailstorm may occur hours, days, months, or, for the purposes of this study, decades in advance. A combination of favorable environmental ingredients must exist in sufficient quantities for the formation of a thunderstorm capable of producing large hail and tornadoes. These ingredients include instability, vertical wind shear, moisture, and a lifting mechanism. CAPE and Convective Inhibition (CIN) are often touted as the instability variables of choice in severe weather analyses. When air parcels have enough positive buoyancy, as measured by CAPE, to overcome negative buoyancy, as measured by CIN, severe thunderstorms occur. Supercell thunderstorms are particularly aided by vertical wind shear, as both faster and turning winds with height promote rotation as well as deep updrafts. In fact, the combination of mixed-layer CAPE and 0-6-km vertical wind shear was shown by Brooks et

al. (2009) to be a good metric for determining the likelihood of significant severe

thunderstorms, and strong vertical wind shear amplifies the potential for hail growth

through the elongation of the storm's updraft and longer the residence time of hailstones

within the cloud (Das 1962, Dennis and Kumjian 2017). A variety of other metrics and

indices have also been used in determining the favorability of the environment toward

severe thunderstorms, including but not limited to storm-relative helicity (SRH; Rasmussen

2003), energy helicity index (EHI; Johns et al. 1993), supercell composite parameter (SCP;

Thompson et al. 2003), significant severe parameter (SSP; Brooks et al. 2003b) and a

combination of convective precipitation and SRH (Tippett et al. 2012). An environment

that is favorable for severe hail is not necessarily one that is favorable for tornadoes,

however. For example, the microphysical aspects of hail growth (and thus the size of the

hailstone) are quite complicated (Edwards and Thompson 1998, Allen et al. 2015a).

Further, Brooks (2013) showed through a phase space of favorable severe weather

environments that, in general, tornadoes and severe hail have similar dependence on

vertical velocity calculated from CAPE and 0-6-km bulk wind difference, yet there are

subtle differences, particularly the relationship of very large hail to vertical velocity and the

sensitivity of tornado formation to low-level moisture. Allen et al. (2020a) examined model

proximity soundings and found surface-based lifted index, mid-level mixing ratio, and

surface dewpoint to be the best parameters for forecasting hail size. Severe hail is also

dependent on the environmental moisture content and the freezing level height; taken

independently, a lower freezing level height and drier air below cloud base both provide a

greater probability for a hailstone to remain intact without much melting or shedding on its

descent to the surface (Rasmussen and Pruppacher 1982, Allen et al. 2015a, Prein and Holland 2018, Trapp et al. 2019).

Mesoanalysis and high-resolution weather models are useful for short-term forecasting of tornadoes and hailstorms, and a variety of teleconnection patterns have been shown to bear some relationship to either U.S. tornado (Thompson and Roundy 2013, Gensini and Marinaro 2016) or severe hail (Barrett and Henley 2015, Gensini and Allen 2018) activity, or both (Baggett et al. 2018) in the 2-5-week timeframe. In addition, the El Niño Southern Oscillation is of use in seasonal prediction of U.S. tornado and severe hail occurrence (e.g. Cook and Schaefer 2008, Allen et al. 2015b, Lepore et al. 2017, Childs et al. 2018). Beyond the seasonal level, two main approaches have surfaced to assess long-term prediction of severe weather: (a) the "ingredients-based approach," which analyzes trends in well-known severe weather parameters, and (b) the "synthetic reports approach," which simulates severe weather events using proxy thresholds. The ingredients-based approach has yielded a general consensus that as the climate warms and moistens, CAPE will increase and vertical wind shear will decrease (e.g. Trapp et al. 2007, Brooks 2013, Diffenbaugh et al. 2013, Seeley and Romps 2015). This conclusion, however, may not apply to all regions, and does not partition according to particular severe weather hazards. Using a pseudo-global warming (PGW) framework, in which a high-emissions (RCP8.5) climate perturbation is applied to high-resolution dynamical downscaling of climate models to compare with control scenarios, Rasmussen et al. (2017) found an increase in radar reflectivity values greater than 40 dBZ and a decrease in radar reflectivity values less than 20 dBZ in the PGW simulation relative to the control for most areas east of the Rocky Mountains. The authors also noted enhanced levels of both CAPE and CIN in the PGW

simulations, and postulated that this supports more vigorous convection, as only the most intense updrafts can break through a tighter atmospheric cap. Chen et al. (2020) also found concurrent increases in CAPE and CIN over most land areas when comparing future (2081-2100) and historical (1980-1999) climate simulations from the Community Climate System Model (CCSM4; Gent et al. 2011), with enhanced CAPE owing to greater low-level specific humidity and enhanced CIN due to lower relative humidity in the future climate. A similar increase in CIN (> 50 J kg^{-1} over the central U.S. in summer months by the end of the 21st century) was noted in climate model output by Hoogewind et al. (2017), but enhanced CIN does not always lead to more intense thunderstorms even with sufficient CAPE. For example, several PGW simulations by Trapp and Hoogewind (2016) that aimed to isolate tornadoes failed to produce any convection due to high CIN. Aside from CAPE and CIN, a future increase in precipitable water downstream of the Rocky Mountains, attributed to enhanced moisture advection from the Gulf of Mexico, was found by Rasmussen et al. (2017). Melting level heights are also expected to continue increasing in the future, owing to a warmer atmosphere (Xie et al. 2010). Taken independently, this favors the melting of hailstones, as a greater layer of above-freezing temperatures exists between the cloud and the ground. However, the largest hailstones, which also have the largest terminal velocities, are not affected as much by melting and thus may become preferential to smaller hail in reaching the surface (Mahoney et al. 2012, Dessens et al. 2015, Brimelow et al. 2017).

The synthetic reports approach to severe storm analysis and forecasting, also called "surrogate severe" (Sobash et al. 2008), is grounded by the argument that any trend in favorable severe weather environments is dependent upon those environments being

realized in a future climate. In this framework, dynamical downscaling of climate model output onto a fine grid using weather models such as WRF is performed to create synthetic severe reports from proxy parameters. Common parameters for general severe weather include a combination of Updraft Helicity and Reflectivity (UH-Z; Trapp et al. 2011, Gensini and Mote 2014, 2015), UH and CAPE (Robinson et al. 2013), UH (Sobash et al. 2016, Sobash and Kain 2017) and Upward Vertical Velocity (UVV; Hoogewind et al. 2017). In addition, UH has proven a useful proxy for tornadoes (Clark et al. 2013, Gallo et al. 2016), and column-integrated graupel (GRPL) for severe hail (Sobash et al. 2011, Trapp et al. 2019).

This study employs the synthetic reports approach using model output from Hoogewind et al. (2017). The global climate model employed is the Geophysical Fluid Dynamics Laboratory Climate Model version 3 (GFDL-CM3; Donner et al. 2011), with the RCP8.5 scenario applied to the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) used for historical and future simulations. Two thirty-year periods are compared representing historical (1971–2000) and future (2071–2100) climates. The GFDL-CM3 model is downscaled using WRF-ARW version 3.6, which is reinitialized each day and gives output every hour over the entire CONUS at 4-km horizontal grid spacing. A subset of model parameters is given in Table 4.2; for a more thorough description, see Hoogewind et al. (2017). The convective proxies include hourly maximums of 2-5-km UH, UVV (in the lowest 400 mb), GRPL, and the Air Force Weather Agency Tornado (AFWATor) and Hail (AFWAHail) parameters. The AFWA parameters are part of a larger group of diagnostics used in the AFWA Mesoscale Ensemble Prediction Suite, which were incorporated into WRF starting with version 3.6 (Creighton et al. 2014) and have been used in various simulations of severe weather events (Martynov et al. 2017, Yavuz et al. 2017)

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and the 2017 NOAA Hazardous Weather Testbed (Gallo et al. 2017). The AFWATor

parameter is a measure of the maximum tornado wind speed (m s^{-1}), and the AFWAHail

parameter approximates the maximum hailstone size. Specifically, these two parameters

are calculated at each time step as follows (Creighton et al. 2014):

AFWATor = Supercell X LLbuoy X LLshear X MidRH, where

Supercell = (2-5-km UH [m² s^{-2}] – 25) / 50,

LLbuoy = (3000 – LFC [m]) / 1500,

LLshear = (0-2000-m wind shear [m s^{-1}] – 2) / 10, and

MidRH = (90 – 3.5-km-AGL RH [%]) / 30;

AFWAHail = (Updraft – Melt – MidRH) X Duration, where

*Updraft = (Vertical Velocity [m s^{-1}] – 1.4) * 1.25*

Melt = 2-m Temperature [K] – 288.15

MidRH = 3.5-km-AGL RH [%] – 70

Duration = (2-5-km UH [m² s^{-2}] / 100) + 0.25

Table 4.2: Description of WRF-ARW version 3.6 model setup used in dynamical downscaling of GFDL-CM3 climate model, after Hoogewind et al. (2017).

PROPERTY	SCHEME / SETUP
Microphysics	Thompson *(Thompson et al. 2008)*
Radiation	RRTM and Dudhia *(Mlawer et al. 1997, Dudhia 1989)*
Boundary Layer	Improved Mellor-Yamada *(Nakanishi and Niino 2004)*
Land Surface	Noah *(Chen and Dudhia 2001)*
Horizontal Grid Spacing	4 km (750 x 1150 grid points)
Vertical Levels	45, top at 1 hPa

Traditionally in synthetic report creation, some threshold is assigned to the parameter of

interest, and a 24-hour period in which that threshold is exceeded over some domain

constitutes a day in which that particular severe weather hazard occurred. This allows a

comparison to be made between severe weather days in historical and future climates.

2. Eastern Colorado projections

To create the control (CTRL) weighting surfaces for use in the MC models, the SPC

tornado and severe hail reports for the period 1997–2017 are first upscaled to a 0.25°

latitude by 0.275° longitude grid across the domain, a procedure that helps to offset the

errors associated with the placement of local storm reports in the SPC database due to

population bias (Hoogewind et al. 2017, Trapp et al. 2019). The annual average number of

tornado and severe hail days within each box is then calculated, and the grids are

converted to shapefiles and then rasterized (Fig. 4.4). Even in this period of relative data

reliability, tornado and particularly severe hail days show a bias toward population centers

along the Front Range, a phenomenon which has been affirmed in various studies and in

Chapter 2 (Allen and Tippett 2015, Potvin et al. 2018, Childs and Schumacher 2019).

Creation of future (FUT) weighting surfaces begins by finding the 99.99 percentile of

each selected convective parameter in the WRF output across the domain for the CTRL

period (1971–2000). The percentiles are then adjusted in one-unit increments until the

number of days in which the threshold is exceeded at least somewhere in the domain most

closely matches the 508 tornado and 955 hail days from the SPC data records in the 1971-

2000 CTRL period. For example, the 99.99 percentile for UH across the domain is 123.875

m² s⁻². This value is adjusted downward to 97.875 m² s⁻², which is exceeded on 513 days in

the CTRL period and thus most closely matches the 508 tornado days. Each threshold
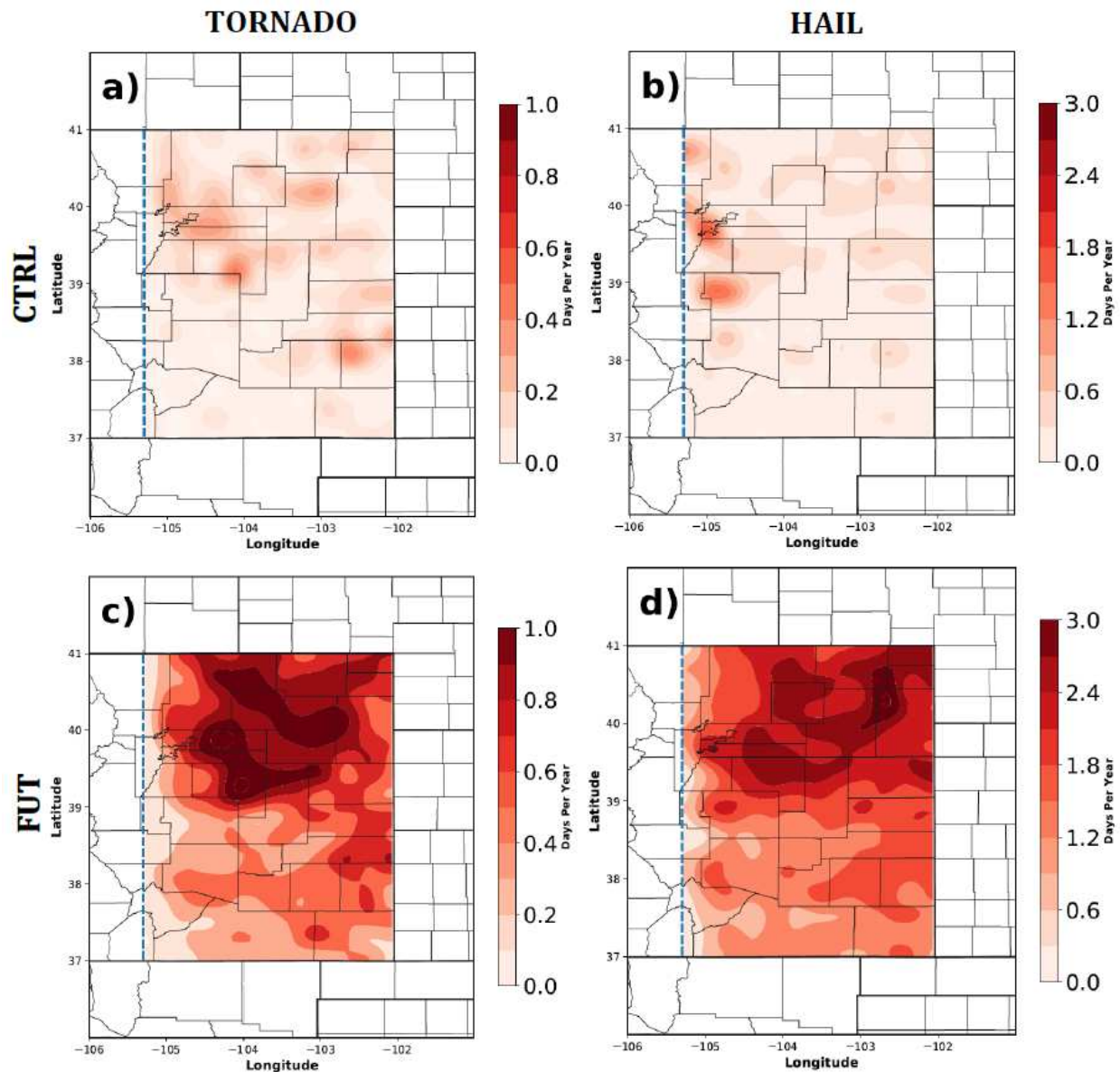
Fig. 4.4: Weighting raster surfaces for tornado (a,c) and severe hail (b,d) events across eastern Colorado. Control surfaces (a,b) are based on 1997–2017 SPC local storm reports converted to tornado and severe hail days, and future surfaces (c,d) are based on synthetic tornado and severe hail days projected for the period 2071–2100 from high-resolution WRF data output.

value computed for the eastern Colorado domain is justified according to the literature or definitions (Table 4.3). These thresholds can provide an estimate of tornado and severe hail days in the CTRL period (1971–2000) by computing the average number of days of threshold exceedances, using AFWATor, UH, and UVV as tornado proxies (Fig. 4.5a) and AFWAHail, UH, UVV, and GRPL as severe hail proxies (Fig. 4.5b). These spatial distributions largely miss the non-meteorological concentration of SPC reports along the urban corridor (Fig. 4.4a,b) since synthetic hazard days do not contain population bias. A few examples of observational and synthetic report alignment is evident, however, such as a relative maximum in tornadoes near the town of Lamar in southeastern Colorado. Recent studies comparing observations of tornadoes (Gensini and Brooks 2018) and severe hail

Table 4.3: Thresholds of each severe weather parameters from WRF output used in the computation of eastern Colorado synthetic reports. Justification from other studies or definitions are given in the rightmost column.

PARAMETER	COMPUTED THRESHOLD	JUSTIFICATION
UH ($m^2 s^2$)	97.875 (Tor), 69.875 (Hail)	• 100 $m^2 s^{-2}$ used in predicting tornado path length (Clark et al. 2012) • ≥60 $m^2 s^{-2}$ found to be optimal for hazardous convective weather events (Gensini and Mote 2014) • ≥40 $m^2 s^{-2}$ used for severe weather occurrence (Trapp et al. 2007)
UVV ($m s^{-1}$)	26.0625 (Tor), 23.0625 (Hail)	• 22 $m s^{-1}$ found to be optimal for hazardous convective weather (Hoogewind et al. 2017)
AFWATor ($m s^{-1}$)	32.75	• Near the middle of EF0 tornado wind speed range (29-38 $m s^{-1}$)
AFWAHail (mm)	28.625	• 25.4 mm (1 inch) is SPC severe criteria
GRPL ($kg m^{-2}$)	26.4375	• 25 $kg m^{-2}$ used as surrogate for 1-inch hail (Gagne et al. 2017, Sobash et al. 2018) • Maximum values of 35-45 $kg m^{-2}$ found in case study of 23 April 2009 hail episode (Kain et al. 2008)
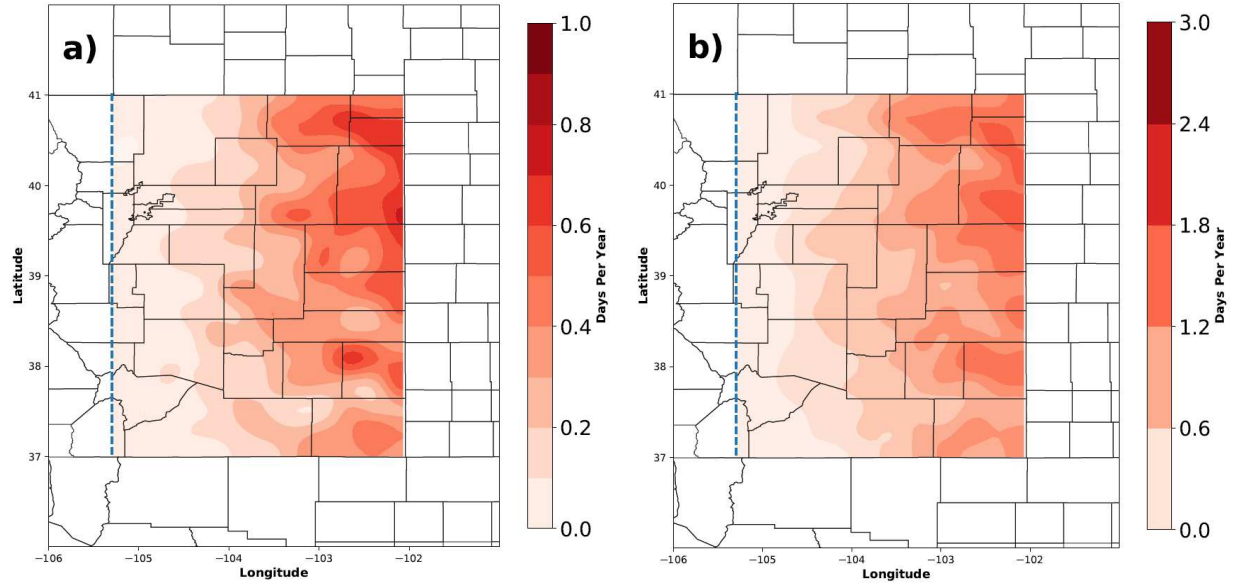
Fig. 4.5: Average number of annual synthetic (a) tornado and (b) severe hail days for the WRF-model CTRL period (1971–2000) over eastern Colorado. Tornado days are computed from an average of daily threshold exceedances of AFWATor, UH, and UVV; severe hail days are computed from an average of daily threshold exceedances of AFWAHail, UH, UVV, and GRPL.

(Tang et al. 2019) also note a mismatch of favorable environments and SPC reports in the immediate lee of the Rocky Mountains, likely due not only to population bias but also the inability of models and reanalysis to correctly capture orographic effects. The approach taken here is to merge observations and synthetic days in creation of future hazard probabilities.

Following threshold computation, the 4-km WRF data output is upscaled to a 0.25° x 0.275° latitude-longitude grid over the eastern Colorado domain to match that of the tornado and severe hail days grids. The number of days that each parameter threshold is exceeded in each grid box over the CTRL (1971-2000) and FUT (2071-2100) periods is tabulated, with the restriction of only one exceedance per time step per grid box, even if

multiple grid points within said box exceed the threshold. Each grid of threshold exceedance is divided by 30 to yield an annual average for both periods, after which the CTRL grid is subtracted from the FUT grid to give the difference in the annual number of threshold exceedances for each parameter. The resulting difference grids for AFWATor, UH, and UVV (Fig. 4.6a-c) are averaged for the tornado hazard (Fig. 4.6d), and the AFWAHail, UH, UVV, and GRPL difference grids (Fig. 4.7a-d) are averaged for severe hail (Fig. 4.7e) to give a measure of the projected spatial change in annual tornado and severe hail days for the 2071–2100 FUT period. Figs. 4.6d and 4.7e reveal that occurrences of synthetic tornado and severe hail reports are projected to increase everywhere across the domain by 2100, with the northern half of eastern Colorado more active relative to the southern half. A similarly oriented arc of maximum annual increase in both hazards stretches across northeastern Colorado, from central Weld County, south to central Elbert County, east to Washington County, and northeast to Sedgwick County (Figs. 4.6d and 4.7e). South of Interstate 70, the increase in annual synthetic report days is more muted, particularly for tornadoes, as almost all grid boxes in the southern half of the domain are projected to see an increase of less than one day per year. It is also apparent that annual severe hail days are projected to increase at least twice as much as tornadoes by the 2071–2100 period.

Individual convective parameters vary in their contribution to changing synthetic tornado and severe hail reports. In general, the UVV difference fields for tornadoes (Fig. 4.6c) and severe hail (Fig. 4.7c) show larger annual increases compared to the UH fields. The AFWATor (Fig. 4.6a) and AFWAHail (Fig. 4.7a) parameters share resemblance to the respective UH and UVV fields, as their formulas contain contributions from UH and UVV.

The greatest magnitude of increasing threshold exceedance in the FUT period for either

hazard is the GRPL parameter (Fig. 4.7d). Almost all grid boxes show at least one more day

per year of GRPL threshold exceedance, with a bull's-eye of greater than 4 days per year

just east of DIA. This result is consistent with Trapp et al. (2019) who showed projections

of up to four days per each summer month of GRPL exceeding their large hail threshold of

25 kg m^{-2} across the western Great Plains on a coarser domain. It should be noted that

since Figs. 4.6d and 4.7e represent averages of three and four proxies, the projected

increase could be an underestimate. In addition, coarser resolution would yield a greater

number of days per year of increase per grid box (Trapp et al. 2019).

Finally, the synthetic tornado and hail grids are added to their respective CTRL

weighting surface to form the FUT weighting surfaces used in the MC models (Fig. 4.4c,d).

These weighting surfaces have a similar spatial distribution to Figs. 4.6d and 4.7e, and

represent enhanced tornado and severe hail probabilities away from the urban corridor

toward northeastern Colorado. Since the FUT weighting surface incorporates both

synthetic reports, which is free from population bias, and the biased SPC storm reports

used in forming the CTRL weighting surface, a more realistic picture of the future hazard

landscape emerges. The percent change in the projected annual number of tornado and

severe hail reports can also be calculated assuming a CTRL-period average of 2.45 and 5.88

tornadoes and severe hail reports per tornado and severe hail day, respectively. This yields

increases of 2.9% more tornadoes and 3.5% more severe hail in the 2071–2100 FUT

period, which are represented in the future MC experiments as an adjustment in tornado

and severe hail annual counts. The small sample size of *significant* tornadoes and hail

reports over this localized domain precludes analysis of changes these larger magnitude
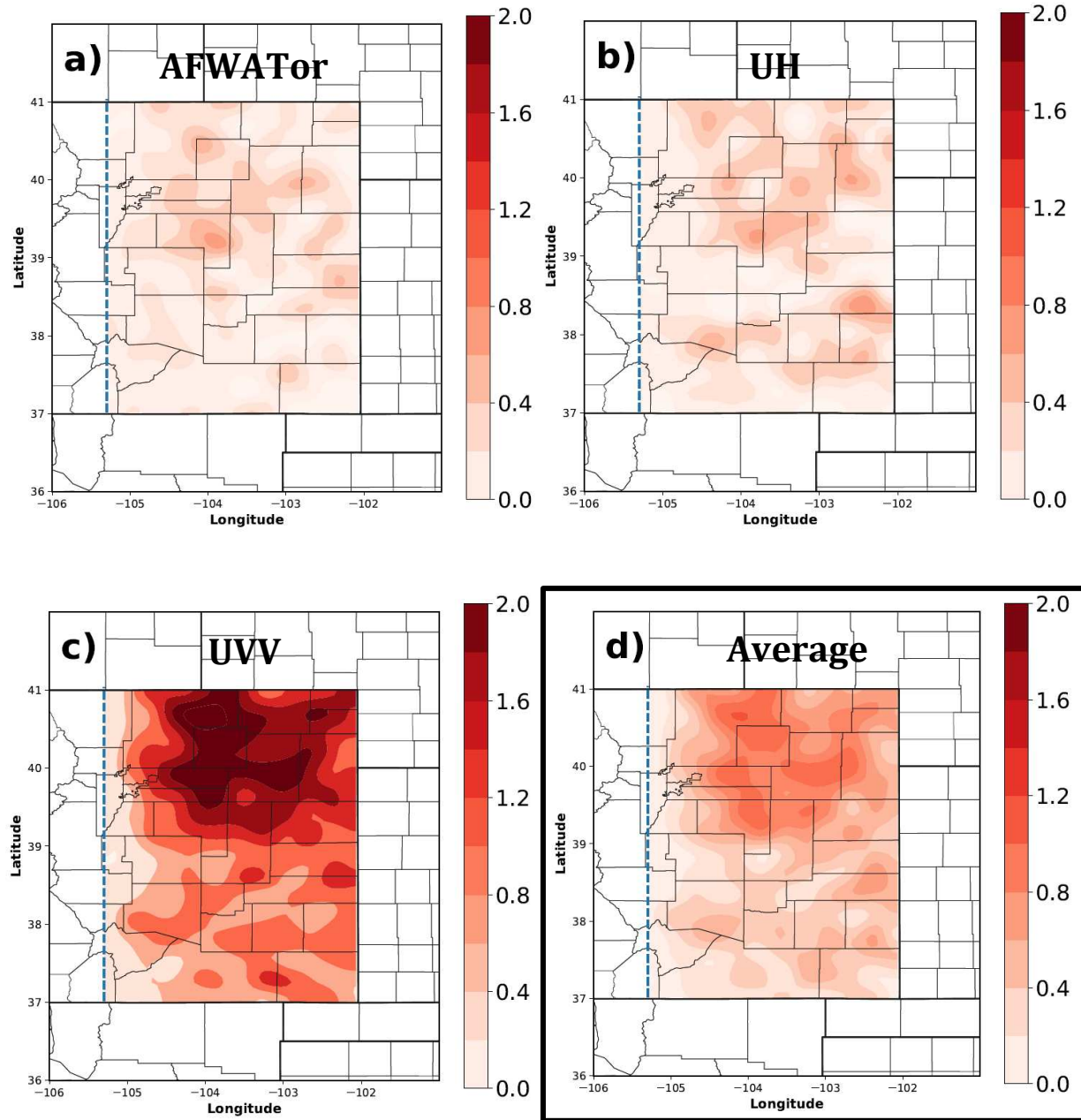
Fig. 4.6: Difference in the number of annual days in which (a) AFWATor > 32.75 m s^{-1}, (b) UH > 97.875 m^2 s^2, and (c) UVV > 26.0625 m s^{-1} between the future (2071–2100) and control (1971–2000) periods. The average of these three grids is given in (d). Grid boxes are 0.25° latitude X 0.275° longitude
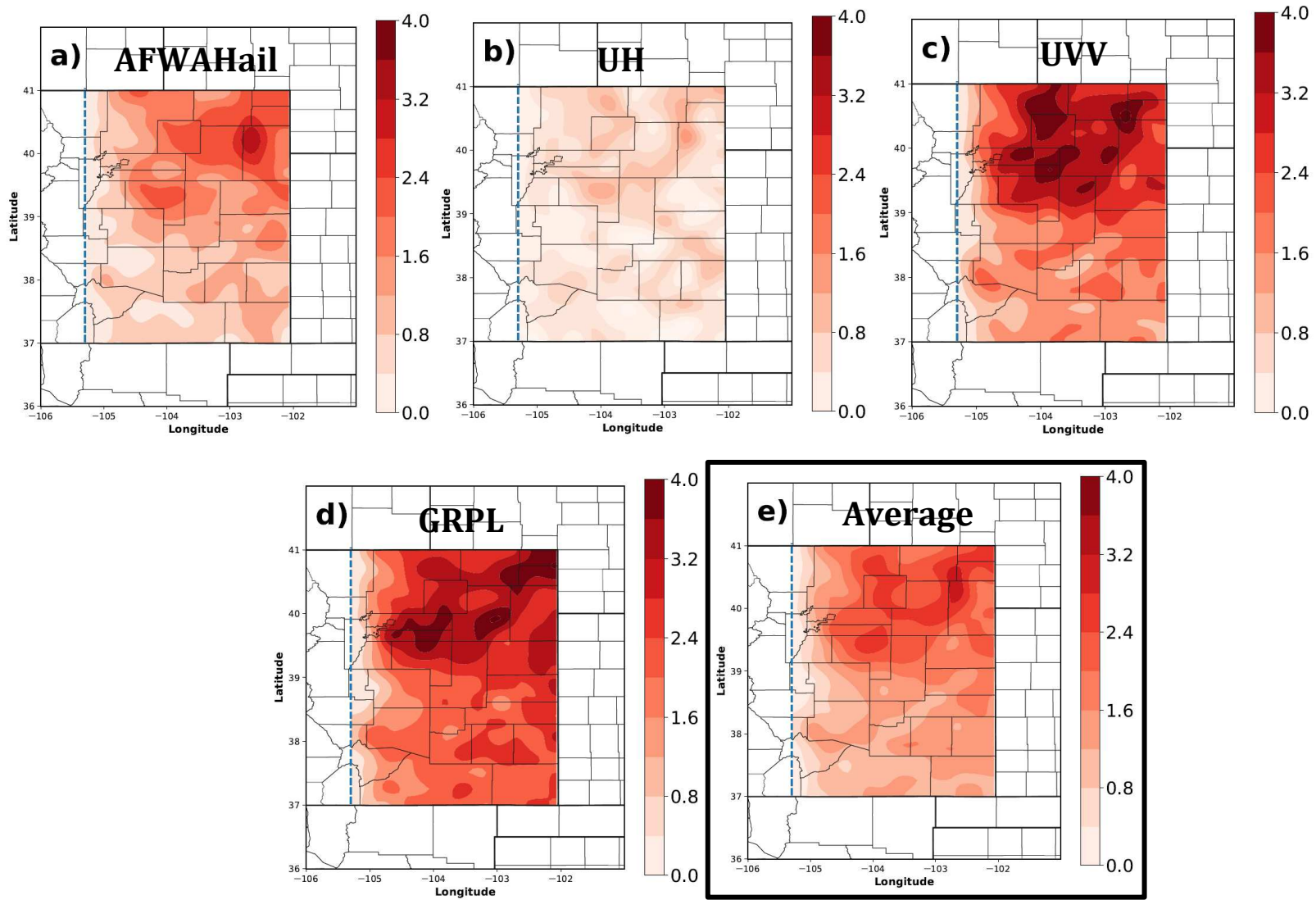
Fig. 4.7: Difference in the number of annual days in which (a) AFWAHail > 28.625 mm, (b) UH > 69.875 m² s², (c) UVV > 23.0625 m s⁻¹, and (d) GRPL > 25.4375 kg m⁻² between the future (2071–2100) and control (1971–2000) periods. The average of these three grids is given in (e). Grid boxes are 0.25° latitude X 0.275° longitude.

events (Childs and Schumacher 2019); these percentages are applied to all event classes and are thus independent of magnitude.

3. Pseudo-global warming perspective

Before using the tornado and severe hail weighting surfaces in a Monte Carlo framework to estimate changes in human exposure, PGW simulations are analyzed to assess control (CTRL) and future (PGW) convective populations and thermodynamic environments. The simulations utilized were run continuously over a 13-yr period (2001-2013) for a CONUS domain (Rasmussen et al. 2017). Table 4.4 showcases key features of the model set-up, detailed in Liu et al. (2017). Like the aforementioned synthetic reports analysis, the CONUS PGW simulations use the WRF model and apply a CMIP5 ensemble monthly mean perturbation under the RCP8.5 scenario for the PGW run. These simulations are forced by ERA-Interim reanalysis every six hours, and spectral nudging is used for synoptic scale fields, allowing mesoscale features to evolve freely. This unique PGW approach has been used to diagnose changes in hurricanes (Gutmann et al. 2018), mesoscale convective systems (Haberlie and Ashley 2019), and extreme rainfall (Prein et al. 2017). Here, for application to severe convective hazards, the output variables of interest are 3-hourly composite reflectivity (dBZ), MLCAPE (J kg^{-1}), and MLCIN (J kg^{-1}), over the eastern Colorado domain. The months of May–August (MJJA) are analyzed, as these four months capture the majority of severe hail and tornado reports across Colorado (Childs and Schumacher 2019). To gauge how composite reflectivity is projected to

Table 4.4: Description of WRF version 3.4.1 model setup used in CONUS simulations of control and PGW environments, after Liu et al. (2017).

PROPERTY	SCHEME / SETUP
Microphysics	Thompson Aerosol-Aware *(Thompson and Eidhammer 2014)*
Radiation	RRTMG *(Iacono et al. 2008)*
Boundary Layer	Yonsei University *(Hong et al. 2006)*
Land Surface	Noah-MP *(Niu et al. 2011)*
Horizontal Grid Spacing	4 km (1360 x 1016 grid points)
Vertical Levels	51, max resolution in PBL
Spectral Nudging	Temperature, Geopotential Height, Winds (above PBL)

change across the domain, 3-hourly values at each grid point (4-km grid spacing) for a select period of MJJA 2010 are binned according to reflectivity threshold and summed cumulatively for both the CTRL and PGW simulations. The year 2010 is selected for its record number of 50.8-mm+ hail reports for the eastern Colorado domain, implying an active convective season. Figure 4.8 shows the percent change in the number of occurrences per reflectivity bin in both MJ and JA from the CTRL to the PGW environments. The results indicate a substantial increase in 50+ dBZ in all months in the future climate. The months of MJ also show increases for all bins greater than 20 dBZ, while JA shows decreases in all bins less than 50 dBZ. On the other hand, both periods show a decrease in the weakest echoes (10-20 dBZ) in the future climate. The magnitude of change is also the greatest on the tails of the reflectivity spectrum, particularly in JA, with the weakest dBZ range decreasing the most and the strongest dBZ range increasing the most, in the PGW

simulation. This result implies a tendency toward more frequent occurrences of the

strongest convection and fewer occurrences of the weakest convection across eastern

Colorado in a future climate, consistent with the larger domain in Rasmussen et al. (2017).
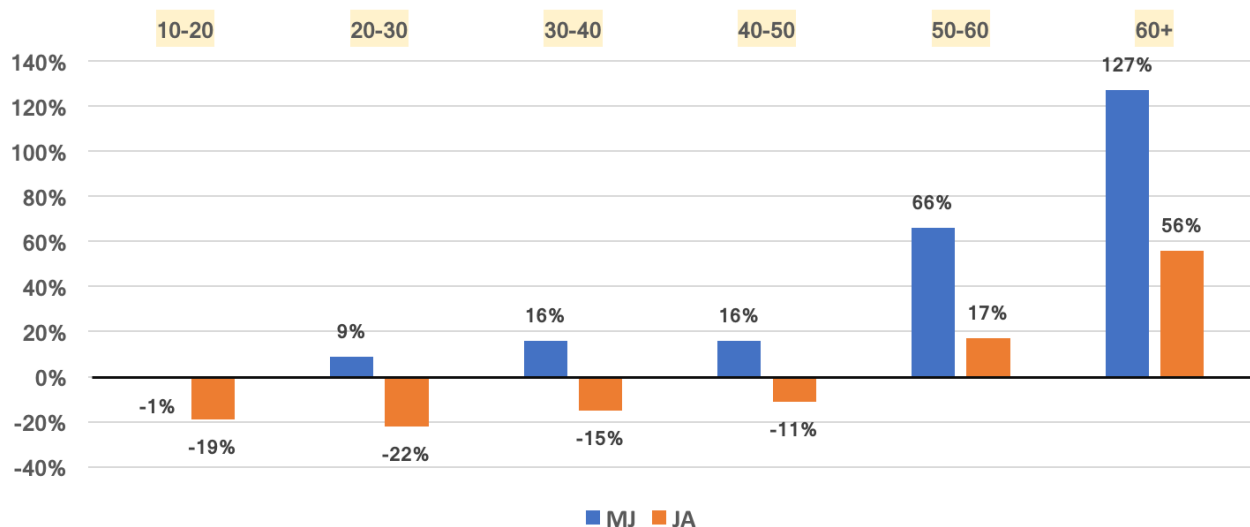
Fig. 4.8: Percent change in the number of 3-hourly reflectivity values (dBZ) within each range for MJ and JA across the eastern Colorado domain from the CTRL to the PGW simulation.

Although a dry bias exists during summer months in the CONUS simulations analyzed in

Rasmussen et al. (2017), this signal is most clear over Midwestern states, and a wet bias

exists in the lee of the Rockies only in the fall months of SON (Liu et al. 2017, Prein et al.

2017).

To complement the reflectivity analysis, MLCAPE and MLCIN values are captured for

the months of MJ and JA over the entire 13-year simulation period (2001–2013) for both

the CTRL and PGW environments. Only the 18, 21, 00, and 03 UTC 3-hourly values are

extracted to account for the diurnal cycle in severe weather reports in the eastern Colorado domain. At each applicable time in which MLCAPE exceeds 500 J kg^{-1} at least somewhere in the domain (to limit instances of scant instability across the entire domain), domain-averaged values of MLCAPE and MLCIN are computed from summing the values at each grid point and dividing by the number of grid points in the domain. The average MLCAPE and MLCIN for each time are then grouped into bins and displayed in the form of a two-monthly 2-D histograms, with bin sizes approximately 83.33 J kg^{-1} and 25 J kg^{-1} for MLCAPE and MLCIN, respectively, and MLCIN values multiplied by -1 to yield positive values. Results are plotted according to the CTRL (Fig. 4.9, left column) and PGW (Fig. 4.9, right column) simulations and by MJ (Fig. 4.9, top row) versus JA (Fig. 4.9, bottom row). The number of applicable times 'n' is also shown for each period. Taking a domain average means that the majority of times have low MLCAPE and low MLCIN in both the CTRL and PGW simulations, hence the concentration of points in the lower-left of the histograms. Another observation is that JA has more instances of elevated MLCAPE and MLCIN compared to MJ. More instructive results are gleaned by taking the difference in distributions for each two-monthly period. Namely, in Fig. 4.10, each CTRL bin has been subtracted from the corresponding PGW bin to yield a difference. For MJ (Fig. 4.10, left), there is a general movement toward higher values of both MLCAPE and MLCIN in the future climate, with bins near the bottom left corner (i.e. low MLCAPE and low MLCIN) seeing the greatest decreases. The pattern is similar for JA, with slight differences in magnitude and slightly less instances of the largest MLCAPE values. The same procedure was also done for the 186 days that had at least eight severe hail reports in the months of
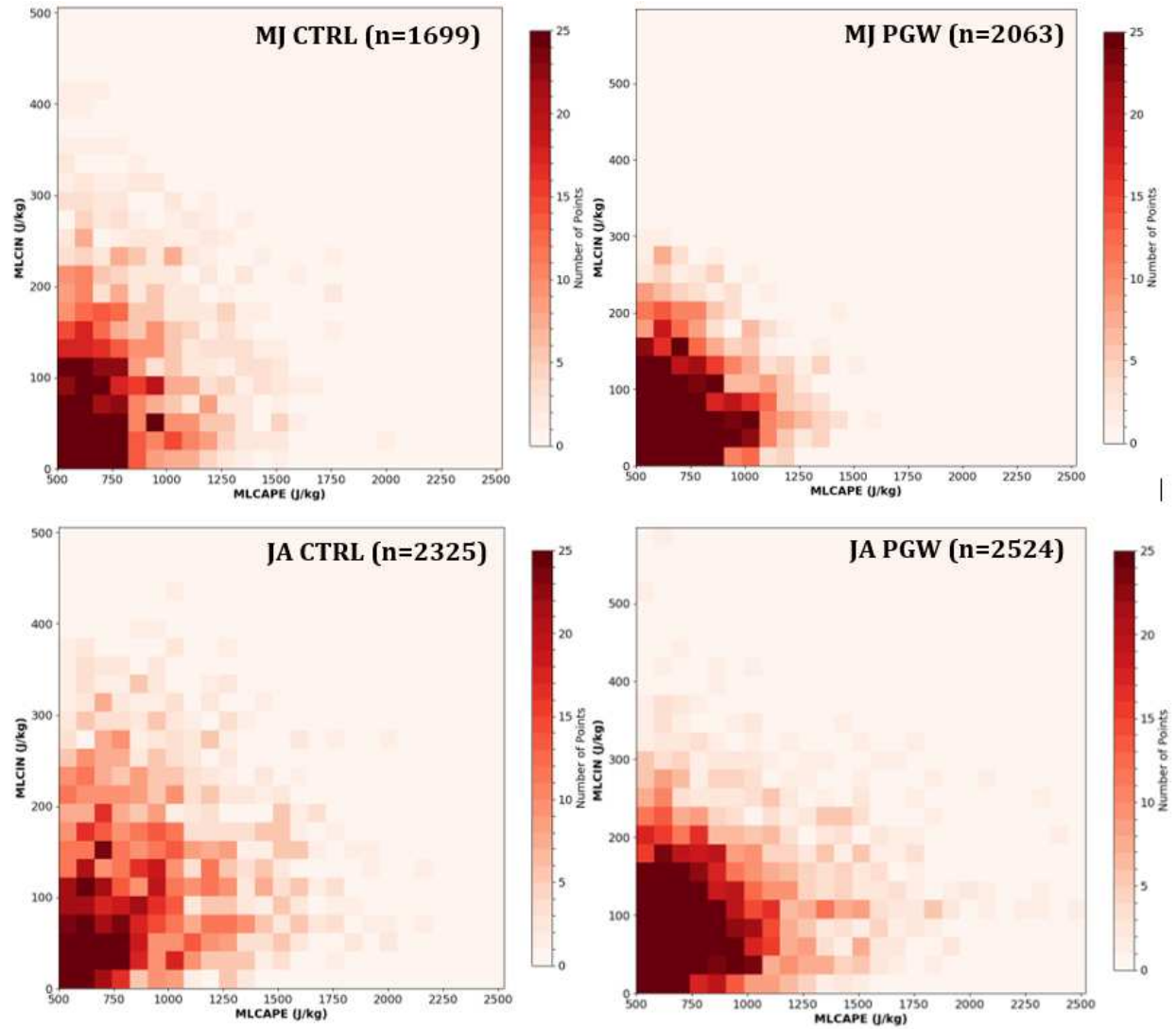
Fig. 4.9: Distribution of domain-averaged simultaneous MLCAPE and MLCIN for model times when MLCAPE exceeds 500 J kg^{-1} at least somewhere in the eastern Colorado domain. The CTRL (PGW) simulation is shown in the left (right) column for the months of MJ (top) and JA (bottom) with the corresponding sample size 'n'.

MJJA during 2001–2013 across the domain, and results were very similar, with a general

movement toward higher CAPE and higher CIN in a future climate. This result is also

affirmative of recent work over much larger domains (Rasmussen et al. 2017, Chen et al.

2020). Physically, enhanced CAPE and CIN implies that there are more environments in the future PGW climate in which there is a large amount of positive buoyancy available for severe convection and more negative buoyancy inhibiting convection from forming, leading to more explosive convection when the atmospheric cap is overcome. A similar conclusion was reached by Brimelow et al. (2017), who noted that enhanced CIN and CAPE in the Great Plains during spring could be responsible for the greater Accumulated Kinetic Energy (AKE), and thus greater potential for damaging hailstorms, over this region in future climate simulations using HAILCAST.
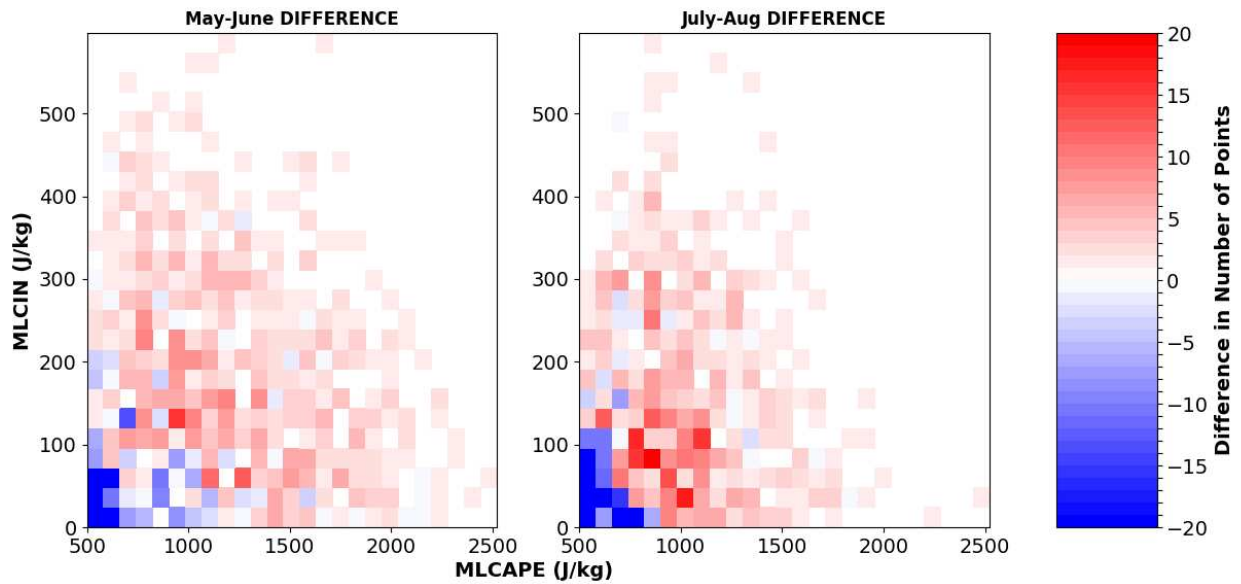
Fig. 4.10: Difference in 2D-histograms of domain-averaged MLCAPE and MLCIN for the period 2001-2013 between PGW and CTRL simulations. Results are shown for the months of MJ (left) and JA (right).

E. Assessment of Human Exposure

1. Base case scenario

Base case MC simulations are run for both tornadoes and hail using the year-2000 GPW cost surface. Tornado and hail events are simulated over 1000 years, and their respective attributes and human exposure are calculated (Table 4.5). The simulated tornado tracks and hail density for the base case (Fig. 4.11) affirms the influence of the CTRL weighting surfaces (Fig. 4.4a,b) on the location of the selected reports. The average of 39 tornadoes per year and 247.5 severe hail events per year simulated by TorMC and HailMC respectively are very close to the actual 1997-2017 means from the SPC data sets (39.0 and 250.6 respectively) and thus capture the current probability. The mean magnitude of tornado events is 0.18, corresponding to an EF0 rating and reflecting the propensity for weak tornadoes across the domain. The average length, width, and azimuth angle are 1.66 km, 35.9 m, and 56.3° (northeastward) respectively, and the base case average hailstone size is 1.38 in (35.1 mm). These statistics do not vary significantly with each new simulation. An average of 34.8 people live within the path of each simulated tornado and 30.2 people within each hail swath, amounting to a mean of 1358 and 7474 and median of 1156 and 1334 persons per year, respectively. The rest of the cases are concerned with the relative change in either hazard occurrence or human exposure out to the year 2100, and thus actual numbers of tornadoes, hail events, and people exposed will not be shown. In order to isolate the individual impacts from population, spatial density of reports, and annual frequency, series of MC simulations are run holding constant one of these variables and adjusting the others based on projected changes.

Table 4.5: Mean tornado and severe hail attributes and human exposure statistics from the base case 1000-yr MC simulations.

Statistic	Tornado	Hail
Annual Count	39.0	247.5
Magnitude	EF0.18	1.38 in
Path Length (km)	1.66	0.5
Path Width (km)	35.9	0.5
Azimuth	56.4°	0°
Human Exposure Per Event	34.8	30.2
Annual Human Exposure	1358	7474

2. Climatological contribution to human exposure

The first set of modified MC simulations explores the relative change in end-of-century human exposure by increasing the annual frequency of tornadoes by 2.9% and severe hail by 3.5% uniformly over the domain. Simulations are conducted with both the CTRL and FUT weighting surfaces to explore whether the projected spatial distribution of events exacerbates human risk further compared to solely changing the frequency of reports. The base case GPW population cost surface is held constant for each of these runs, presenting a theoretical future where no population or built-environment changes occurs. In these scenarios, mean annual counts increase by at least 2.2% for tornadoes and 3.8% for severe hail (Table 4.6), consistent with the projected amplification in frequency applied to the MC models. The slight differences in percent increase are due to the random nature
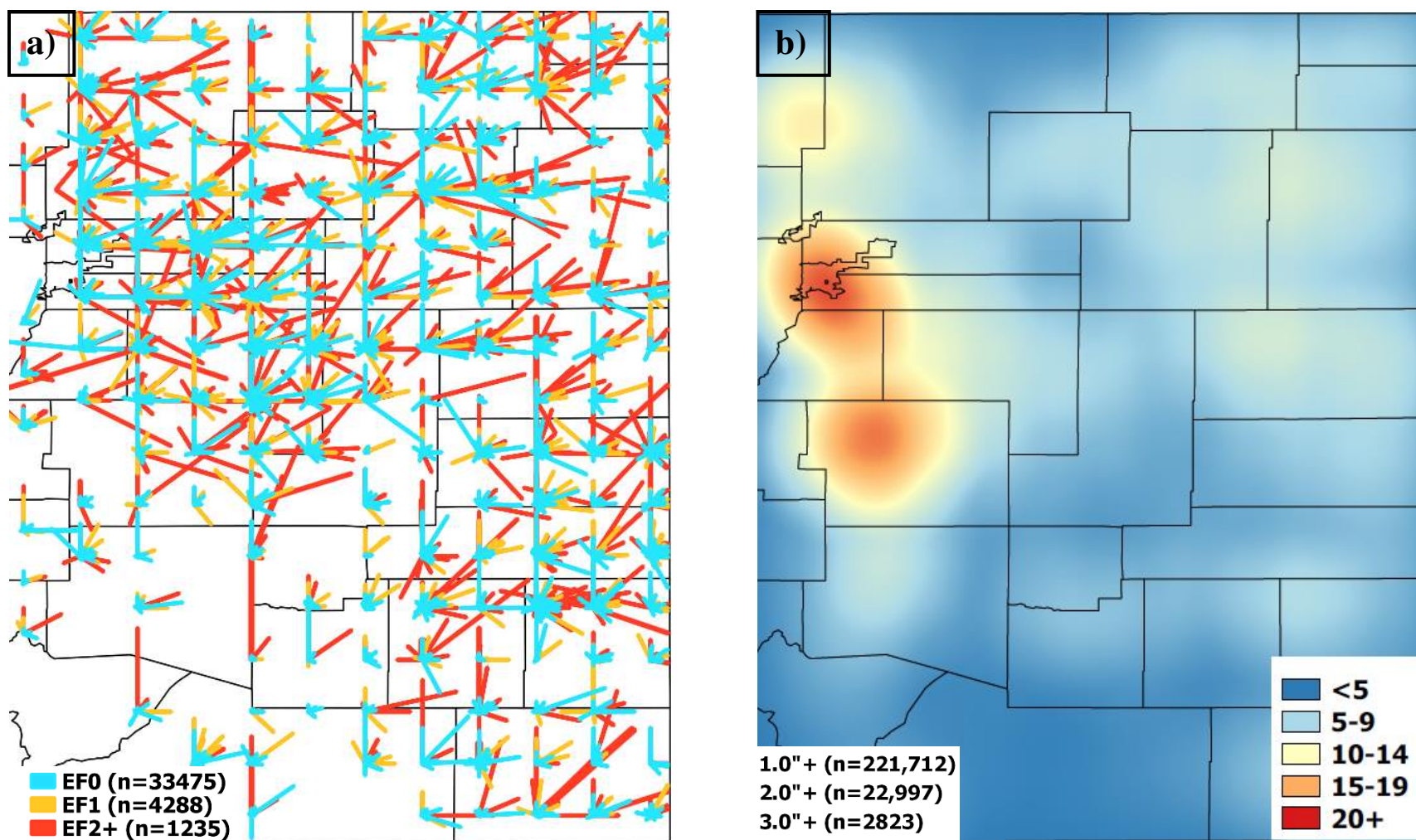
Fig. 4.11: (a) Simulated tornado tracks, partitioned by EF-scale intensity, and (b) Heat map of simulated severe hail swaths using kernel density estimation, where the darkest shading represents in excess of 20 reports per year, for the base case scenarios within TorMC and HailMC.

of the MC simulation and not the spatial weighting surface.

Table 4.6: Annual tornado and severe hail statistics for scenarios with constant base case population cost surface.

Scenario			Annual Tornado Statistics				
Cost Surface	Frequency	Spatial Weighting	Mean	Change in Mean	Max	Median	Std. Dev.
Base case	Control	Control	39.0	-	78	37	16.8
Base case	+2.9%	Control	39.8	**+2.2%**	80	38	17.4
Base case	+2.9%	Future	40.2	**+3.1%**	80	38	16.6
			Annual Severe Hail Statistics				
Base case	Control	Control	247.5	-	468	213	100
Base case	+3.5%	Control	259.2	**+4.7%**	484	220	107
Base case	+3.5%	Future	257.0	**+3.8%**	484	220	102

Of greater interest are changes in annual human exposure attributed to changes in climatological probability of occurrence independent of population (Tables 4.7 and 4.8, top block of rows). An increase in tornado and hail frequencies paired with the control spatial probabilities results in 6.2% and 6.3% greater human exposure per year respectively by the end of the century. However, increasing the hazard and applying the FUT weighting surface results in a decrease in human exposure of 14.6% and 75.7% for tornadoes and severe hail respectively. This is attributed to an apparent shift in future tornado and hail event frequencies toward eastern Colorado where population density is low. Thus, tornado and hail exposure under this future scenario is expected to decrease.

3. Population contribution to human exposure

This section controls for any potential future changes in tornado and hail environments while allowing future population to evolve throughout eastern Colorado (Tables 4.7 and 4.8, second block of rows). All population growth scenarios except SSP3 lead to a substantial increase in human exposure. Although a range of potential changes is revealed, the SSP5 produces a 154.6% increase in tornado exposure and a 161.0% escalation in severe hail exposure. Conversely, SSP3 reduces mean annual human exposure to tornadoes by 8.4% and slightly increases human exposure to severe hail by 0.1%. To recall, SSP5 produces widespread population growth across eastern Colorado, particularly along the urban corridor, and SSP3 produces only small pockets of growth in metropolitan areas alongside areas of decreasing population; hence the spread in potential end-of-century human exposure. Comparing these statistics with those in Table 4.6, where population is held constant, it is apparent that changes in population (except the SSP3 scenario) exert a greater influence on human exposure than climatological changes in tornado and severe hail landscapes. This result agrees qualitatively with Strader et al. (2017), who found that changes in the number of housing units outweighed changes in tornado occurrence toward increasing overall risk.

4. Mutual contribution to human exposure

Finally, two series of simulations are employed to investigate the mutual contribution of climatological and population changes on end-of-century human exposure (Tables 4.7 and 4.8, third block of rows). In the first set of simulations, each SSP surface is overlain on top of tornado and severe hail surfaces that have been generated by altering

Table 4.7: Annual human exposure to tornadoes across eastern Colorado. Different cases are simulated by varying the cost surface of SSP population scenarios, the frequency of tornadoes as projected by the WRF analysis, and the spatial probability surface of either historical data or the projected synthetic reports distributions. Aside from the percent change in the annual mean, the units shown are number of people.

Scenario			Annual Human Exposure				
Cost Surface	Frequency	Spatial Weighting	Mean	**Change in Mean**	Maximum	Median	Standard Deviation
Base case	Control	Control	1358	-	25,991	449	3056
Base case	+2.9%	Control	1442	**+6.2%**	79,663	428	4516
Base case	+2.9%	Future	1159	**-14.6%**	61,011	332	3735
SSP1	Control	Control	2240	**+65.0%**	47,624	583	5590
SSP2	Control	Control	2201	**+62.1%**	46,864	569	5503
SSP3	Control	Control	1244	**-8.4%**	27,330	285	3220
SSP4	Control	Control	1742	**+28.3%**	37,558	431	4418
SSP5	Control	Control	3457	**+154.6%**	71,277	989	8348
SSP1	+2.9%	Control	2413	**+77.7%**	147,176	543	8324
SSP2	+2.9%	Control	2371	**+74.6%**	144,890	529	8195
SSP3	+2.9%	Control	1347	**-0.8%**	84,888	259	4805
SSP4	+2.9%	Control	1881	**+38.5%**	116,373	393	6585
SSP5	+2.9%	Control	3707	**+173.0%**	219,367	930	12,396
SSP1	+2.9%	Future	1914	**+40.9%**	113,001	427	6865
SSP2	+2.9%	Future	1881	**+38.5%**	111,256	417	6760
SSP3	+2.9%	Future	1067	**-21.4%**	65,187	210	3960
SSP4	+2.9%	Future	1491	**+9.8%**	89,353	315	5429
SSP5	+2.9%	Future	2943	**+116.7%**	168,411	720	10,234

the frequency of these hazards but retaining the CTRL hazard spatial distribution.

Escalating the frequency of tornadoes is not sufficient to overcome the decreasing

population patterns in SSP3, resulting in a smaller human exposure compared to the base

case. For all other SSPs, human exposure increases slightly over the changing population-

constant risk scenarios, by as much as 173.0% with SSP5. When both frequency and spatial

distribution of tornadoes are modified (Table 4.7, bottom block of rows), the resulting

change in human exposure is lower for each SSP compared to solely changing the tornado

Table 4.8: As in Table 4.7, but for annual human exposure to severe hailstorms.

Scenario			Annual Human Exposure				
Cost Surface	Frequency	Spatial Weighting	Mean	**Change in Mean**	Maximum	Median	Standard Deviation
Base case	Control	Control	7474	-	20,979	6746	3539
Base case	+3.5%	Control	7947	**+6.3%**	22,956	7201	3849
Base case	+3.5%	Future	1816	**-75.7%**	6769	1587	1053
SSP1	Control	Control	13,028	**+74.3%**	37,180	11,718	6251
SSP2	Control	Control	12,827	**+71.6%**	36,622	11,539	6156
SSP3	Control	Control	7485	**+0.1%**	21,494	6731	3610
SSP4	Control	Control	10,297	**+37.8%**	29,468	9254	4952
SSP5	Control	Control	19,509	**+161.0%**	55,355	17,574	9315
SSP1	+3.5%	Control	13,858	**+85.4%**	40,665	12,589	6087
SSP2	+3.5%	Control	13,646	**+82.6%**	40,053	12,398	6705
SSP3	+3.5%	Control	7964	**+6.6%**	23,496	7260	3933
SSP4	+3.5%	Control	10,955	**+46.6%**	32,221	9972	5394
SSP5	+3.5%	Control	20,749	**+177.6%**	60,569	18,829	10,141
SSP1	+3.5%	Future	2877	**-61.5%**	11,384	2498	1794
SSP2	+3.5%	Future	2825	**-62.2%**	11,196	2452	1765
SSP3	+3.5%	Future	1590	**-78.7%**	6451	1382	1024
SSP4	+3.5%	Future	2234	**-70.1%**	8941	1940	1413
SSP5	+3.5%	Future	4459	**-40.3%**	17,263	3899	2705

frequency. Nevertheless, each SSP aside from SSP3 (-21.4%) still yields an appreciable

amplification in human exposure relative to the base case.

Raising the probability of severe hail over the domain (Table 4.8, third block of

rows), in addition to population changes, results in a greater mean annual human exposure

by as much as 177.6% over the base case scenario. In fact, all SSPs yield a quantitatively

larger increase in human exposure compared to when the future hail frequency is applied

to the base case scenario, once again affirming a strong population influence on the number

of persons exposed to the hazard. When all factors are allowed to change, a decrease in

human exposure is predicted for each SSP relative to the base case scenario, from -40.3% for SSP5 to -78.7% for SSP3 (Table 4.8, bottom block of rows). The eastward shift of the largest frequencies of severe hail in the future into less populated areas is responsible for this reduction.

F. Discussion and Implications

Understanding potential future changes in both population and tornado/severe hail landscapes is crucial to forecasting future human risk and the associated impacts. Eastern Colorado in particular, presents a unique region for this work. Not only does this region have one of the fastest growing metropolitan areas alongside an extensive rural area, but it also represents one of the most active tornado and severe hail regions of the U.S. That said, the methods presented herein may be applied to other regions across the U.S. to reveal other local trends in both meteorological and non-meteorological variables that can influence local severe weather risk.

The projected population distributions and hazard landscapes across eastern Colorado present a wide range of potential end-of-century tornado and hail exposure outcomes based on the MC results presented in this study. Examining future tornado and hail events, the synthetic reports approach predicts only a marginal increase in the number of tornado and severe hail days across eastern Colorado by 2100. This base case future tornado and hail scenario results in only modest increases in human exposure to these hazards. If the hazards were to increase above projected levels within eastern Colorado, higher risks will result. Assuming the current means of 2.5 tornado reports and 5.9 hail reports per tornado and hail day respectively remains constant, up to 2.5 additional

tornado and 18 additional hail reports per year can be expected in those grid boxes with the greatest frequency of tornadoes or hail. These findings are in line with Childs and Schumacher (2019), who reported increasing trends in severe hail reports and hail days at all size thresholds within the eastern Colorado region since 1997, and Trapp et al. (2019) who showed projected future increases in large hail frequency over this region using dynamical downscaling techniques. Together, these studies suggest that if the future hail event scenarios are realized, not only could more hail be reported in northeastern Colorado, but a greater number of significant hailstones could also fall on more days.

In general, most parameters used as proxies for tornado and severe hail events indicate a future increase in frequency domain-wide, maximized in northeastern Colorado. However, this eastward shift leads to decreasing human exposure to severe hail relative to the base case scenario and a smaller increase in exposure to tornadoes relative to scenarios that use the CTRL spatial distribution. Changing the spatial distribution of hazards according to projections from high-resolution weather model output is unique to this study, as previous work by Strader et al. (2017) experimented with the same change in frequency over their entire domain of interest. Along the Front Range urban corridor, the number of tornado and severe hail days are also projected to increase, just not as much. Thus, one would still expect to see an escalating number of tornado and hail reports in these populated areas. In particular, areas east of downtown Denver have experienced significant growth in the past five years, as hotels, restaurants, and a major resort have strategically moved into the area to serve as a gateway to the airport. It is inevitable that housing will continue to expand into this area as well, which will not only add to the built environment but also put people into a zone of enhanced tornado and hail risk. In addition,

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the SSP1, SSP2, and SSP5 scenarios show appreciable growth around Fort Morgan in northeastern Colorado, which is within the maximum projected increase in both tornado and severe hail occurrence; if population does indeed grow in this area, there would be a need to raise public awareness of the heightened risk from these hazards.

The eastward shift in projected severe hail frequency, though producing decreased human exposure, does result in a greater number of hailstorms affecting agricultural land. Crop losses from hailstorms not only reduces yields but also places stresses on the market, as some $41 billion dollars is contributed from the agricultural sector to the Colorado economy each year (CSU 2012). Recent high-resolution land use projections across the Great Plains from the U.S. Geological Survey (Sohl et al. 2018) can be used to support this hypothesized projected rise in agricultural exposure. Inputting their base case (year 2014) land use surface for a "business-as-usual" climate scenario, clipped to the eastern Colorado domain, into HailMC results in a 14% increase in the amount of agricultural land exposed to hailstorms on any given year by the end of this century using the FUT hail weighting surface. Future work is warranted to assess how changes in agricultural land use patterns may impact crop exposure to severe weather hazards. Toward this end, an interview study was conducted in Summer 2019 with eastern Colorado agriculturalists, with the goal of increasing awareness of the needs and vulnerabilities of the agrarian population toward severe hailstorms (Childs et al. 2020b, accepted pending revision). This work, which is the topic of Chapter 5, becomes even more important in light of the MC results presented here.

While population growth and urban expansion are likely to continue, there are steps that can be taken as people continue to move into areas that are projected to be at greater

risk from tornadoes and hailstorms in the future. Arguably of first priority is increasing

public awareness, which must be wrought with intentional and planned endeavors.

Especially in largely rural areas like eastern Colorado, risk communication faces numerous

challenges. People moving into the state from elsewhere for business, retirement, or

recreation purposes may be unaware that Colorado is in fact a state prone to tornadoes and

damaging hailstorms since it is not in the traditional "Tornado Alley" or the Southeast.

Thus, newcomers must be made aware of the risk so they can make informed decisions

about living location, types and amount of insurance to buy, and protective measures to

take. It is through the synthesis of research and communication that the local public can be

informed of the changing risk from severe weather and the negative impacts of such

hazards can be mitigated.

G. Conclusion

This study offers a first look at how population and meteorology work separately

and together to modify human exposure by the end of the 21st century across the localized

domain of eastern Colorado. A wide range of potential changes in the number of people

exposed to these hazards is revealed. Two MC models are utilized that repeatedly sample

tornado and severe hail events according to spatial probabilities of these hazards over

eastern Colorado in a current and future climate. Projections of severe weather hazards

out to the year 2100 have been made through a synthetic reports approach, wherein

convective parameters serving as proxies for tornado and severe hail reports are compared

between two high-resolution WRF simulations of current and future climate scenarios

(Hoogewind et al. 2017). This analysis predicts a domain-wide increase in the average

annual tornado and severe hail days by the end of this century, with up to one more day of

tornadoes and three more days of severe hail per year by this time. Maximum increases in both hazards are concentrated in an arc across northeastern Colorado with subtle yet noteworthy differences.

Population projections out to the year 2100 are taken from the SSPs and cropped to the eastern Colorado domain. Most SSPs project increasing population along the Front Range urban corridor with lesser change further east, but key differences exist in both magnitude and spatial patterns that influence the number of people potentially exposed to the severe weather hazards. MC simulations are run for 1000 years and reveal that future human exposure is highly dependent upon population dynamics and the spatial distribution of hazards, particularly for hail. Alternating population scenarios in constant hazard results in a broad spectrum of changes in end-of-century annual mean human exposure, ranging from -8.4% to +154.6% for tornadoes and +0.1% to +161.0% for severe hail. The largest magnitude of increase in projected human exposure for both hazards occurs when population and frequency of the hazard changes but the spatial distribution is held at the historical state. Under this scenario, a 177.6% increase in human exposure to severe hail is predicted by 2100. When spatial distribution of tornado and hail hazards are incorporated, a decline in human exposure is projected. This affirms the sensitivity of the human system to changes in meteorology; despite climate change signals, the amount of risk actually has the potential to decrease in local contexts due to the overlapping effect of meteorological and population changes. The implications of this sensitivity on policy makers is important, as determination of future risk for local communities and the associated mitigation strategies must consider these distinct possibilities.

This study acknowledges a wide range of uncertainty with exactly how many people in eastern Colorado will be exposed to tornadoes and severe hail in the future, and it is not of interest to predict which scenario is the most probable. While it is reasonable to posit continued population growth and eastward expansion of the Front Range urban corridor, many factors, some unforeseen, could influence future population distribution within the domain. Further, the synthetic reports approach taken here is one of a variety of potential methods to project frequency and spatial distributions of tornadoes and severe hail. This study also cannot completely avoid the population bias inherent in the SPC severe weather database, although the use of tornado and severe hail days as the measure of hazard frequency and convective parameters as proxies for reports can better capture the changing distribution of favorable severe weather predictors. It should also be mentioned that an increasing human exposure does not necessarily mean increasing human injuries, fatalities, or property losses. The hope is that increasing awareness of potential changes in exposure, the continued technological advancements in long- and short-term severe weather forecasting, and improved mitigation strategies by a wide variety of local sectors can help avert more serious human and property impacts. For example, land use and urban planners can develop growth strategies in light of the changing severe weather landscape. New building construction and the associated building codes should address the evolving hazard risk, particularly in areas of increased exposure such as near DIA, as strict building codes have shown promise in reducing hail risk (Czajkowski and Simmons 2014). Relatedly, vulnerable entities such as automobile dealerships and recreation areas in Colorado that have suffered extensive damage from hailstorms in recent years have taken steps toward hazard mitigation (CBS4 Denver 2019, Greeley Tribune 2019). In light

of the projected amplified hazard probabilities in rural areas of the eastern Plains, agricultural interests should work to implement alternative crops that are more resilient to severe weather impacts, knowing that crop insurance, although arguably the most effective mitigative strategy for farmers, is not an end-all solution. It is also imperative that a changing hazard risk and exposure be communicated to the local population in a comprehensible manner. Meteorologists play a critical role in providing this effective communication and can also benefit from projections of future human exposure as they work to continue advancements in tornado and hailstorm predictability. Given the wide range of potential changes in human exposure, and in turn the human risk, residents of eastern Colorado are encouraged to take steps now to prepare for future tornadoes and hailstorms.

CHAPTER 5: AGRICULTURALIST PERSPECTIVES ON SEVERE HAIL RISKS AND WARNING

MESSAGING: AN INTERVIEW STUDY OF EASTERN COLORADO FARMERS AND RANCHERS[6]

A. Background

As motivated in previous chapters, there is no shortage of literature and analysis on

the environments supportive of hailstorms, as well as climatological statistics such as

frequency, seasonality, and spatial distribution (Changnon 1977, Changnon and Changnon

2000, Allen and Tippett 2015, Allen et al. 2015, Lepore et al. 2018, Allen et al. 2020b).

What is less understood are the human perceptions of and responses to hailstorms and

their associated impacts. For example, what is seen as the greatest risk from hailstorms?

How do people measure hailstorm severity – is it by size, damage, or some other metric?

How is one's exposure and sensitivity to hailstorms changing over time? How do people

perceive the effectiveness and applicability of warning messages for severe hail? Gaining

an understanding of these topics and others can lead to more effective risk communication,

endeavors to support the most vulnerable, and future research pathways to study

hailstorm characteristics. This study is the first to specifically investigate hailstorm

perceptions through the lens of the sector of society arguably most affected by natural

hazards in day-to-day operations, namely agriculture. As such, fifteen semi-structured

interviews were conducted with farmers and ranchers who live and work across eastern

Colorado.

As discussed at length in Chapter 2, Colorado lies within the area of enhanced

hailstorm activity within the U.S., and has seen some particularly damaging hailstorms in

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[6] Adapted from Childs et al. (2020b, *WCAS*, accepted pending revision)

recent years. The 8 May 2017 Denver event became the second costliest hailstorm in U.S. history with an estimated $2.3 billion in damage, an 6 August 2018 hailstorm killed five animals and injured close to a dozen people at the Cheyenne Mountain Zoo in Colorado Springs (Childs and Schumacher 2018b), and on 13 August 2019, the largest hailstone in state history was measured at 4.83 in (122.6 mm) in Kit Carson County in far eastern Colorado. According to the Rocky Mountain Insurance Information Association (RMIIA), Colorado trailed only Texas in the most hail claims for the period 2003-2015, and in 2018 Colorado topped auto and homeowners hail claims with over $598 million (State Farm 2019). While large hailstones (e.g., those in excess of 25.4 mm) tend to lead to the most physical damage, so-called plowable hailstorms, in which hail accumulates to appreciable depths and requires snow plows for its removal, can also cause substantial damage and travel interruptions across Colorado (Kalina et al. 2016, Friedrich et al. 2019). As reported in Chapter 2, the eastern half of Colorado has seen an increasing trend in hail reports and hail days at all size thresholds since 1997 (Childs and Schumacher 2019), an era in which severe weather data is more reliable due to standardized reporting practices and implementation of Doppler radar (Agee and Childs 2014, Allen and Tippett 2015). This increasing trend is in contrast to national-level hail trends, which were essentially flat over the period 1997–2014 (Allen and Tippett 2015). There also exists an increasing proportion of 2.0-in+ (50.8-mm+) and 3.0-in+ (76.2-mm+) hail reports relative to all severe hail reports (1.0 in; 25.4 mm) across eastern Colorado since 1997; in 2018, one-fifth of all severe hail reports in this region were at least 50.8 mm in diameter (Childs and Schumacher 2019).

Eastern Colorado is also unique in its mix of urban centers along the Front Range adjacent to a vast area of sparsely populated agricultural land. This dichotomy showcases the population bias inherent within hail data. For a hailstone report to be tallied, a trained spotter, storm chaser, or member of the public must collect the hail, measure it, and send the information to the local NWS office, often with a picture. This requires that people be in close proximity to where hail is falling, which by default is much easier in populated areas. This leads to a disproportionate amount of hail reports in cities, while many hailstones that fall in rural areas go unreported for lack of population. The eastern plains of Colorado also feature a relatively small gridded network of paved roads, which shows up on the map of hail reports as north-south and east-west lines (Fig. 2.10).

Hailstorms that affect rural areas also tend to garner less media attention, but it is here where hailstorms can cause significant agricultural impact. One hailstorm has the potential to wipe out an entire field, leading to sizeable losses both financially and in crop yield (Lemons 1942, Changnon 1971, Shapiro et al. 1986, Lollato et al. 2017, Battaglia et al. 2019). In addition, rural agricultural areas often face higher vulnerabilities and reduced adaptive capacity to climate and weather hazards (Kapucu et al. 2013, Cox and Hamlen 2015). With agricultural output contributing $41 billion to Colorado's economy each year (CSU 2012), and some 90% of Coloradoans reporting that their quality of life is improved because of agriculture (CDA 2016), any hindrance to achieving maximum yield can result in local economic instability.

In recent years, the U.S. agricultural sector has been the subject of much research investigating perceptions of climate change and its impacts on applicable natural hazards. A slight majority of farmers believe that climate change is occurring (Arbuckle et al. 2013,

Prokopy et al. 2015b), although mixed perceptions exist among farmers as to whether the main driver of climate change is anthropogenic (Arbuckle et al. 2014, Prokopy et al. 2015b), and Prokopy et al. (2015a) found that climate and agricultural scientists are nearly four times more likely to believe in anthropogenically caused climate change than are farmers. Interestingly, despite a general concern for climate change impacts on weather patterns that affect crop yields, the majority of U.S. farmers agree that adaptation strategies can overcome adverse effects (Arbuckle et al. 2013, Prokopy et al. 2015b). At the local scale, Lane et al. (2018) held focus groups of farmers in New York and Pennsylvania and revealed a concern that a new normal is emerging in which extreme events – specifically drought and heavy rainfall – are becoming more frequent. Similarly, farmers in Vermont are concerned about climate change intensifying existing risks, specifically citing floods as a worsening weather risk (Schattman et al. 2016). The samples in these two studies also felt concern for secondary effects such as soil erosion and market stress. Moreover, in a survey of Midwest U.S. farmers, the majority of respondents cited an increase in variable and unusual weather patterns in the past five years, with the greatest concerns being extended drought and heat stress (Mase et al. 2017).

Unlike the hazards of drought, extreme heat, and to some degree flooding, which exacerbate slowly over a growing season or several growing seasons, a hailstorm is an isolated event that can produce the same end result (i.e., a destroyed crop) in a matter of minutes. This means that any changes in frequency or severity will be felt more tangibly on an annual basis by farmers. Moreover, hailstorms can damage equipment and pose risks to people working in the fields. Despite these distinctive attributes, research is lacking on agricultural perceptions of the hailstorm hazard and associated vulnerabilities and

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mitigation strategies. Some studies outside of the U.S. have measured how farmers

perceive and adapt to hailstorms, including in China (Zheng and Byg 2014), India, and

Nepal (Choudhary et al. 2012, Paudel et al. 2014, Shukla et al. 2016), and Italy (Menapace et

al. 2015). However, to our knowledge, this is the first modern study to specifically measure

hailstorm perceptions in a region of the U.S. within the farming industry.

In the U.S., "severe" hail is formally defined as being at least 25.4 mm in diameter.

This threshold was adjusted upward from 19.1 mm in 2010 after input from media and

stakeholders suggested that appreciable property damage does not occur until hail is at

least 25.4 mm (NCEI 2009, NWS 2010). There currently does not exist a 'Severe Hail

Warning' issued by the NWS; rather, when severe hail is indicated via radar or trained

spotters, a Severe Thunderstorm Warning (SVR) bulletin will be issued. These warnings

always include the anticipated hailstone size and sometimes include a special tag

recommending protective actions if significant impacts are expected. A note about sub-

severe hail can be included in a SVR for wind gusts, but never is a SVR issued for hail alone

that is less than the 25.4-mm threshold. To our knowledge, there has not been a formal

investigation of users' perceptions of this "severe" hail threshold used in warning

messages, or the evaluation of how SVR for hail are received and acted upon. Much of the

existing literature on public reception of severe storm warnings has instead focused on

Tornado Warnings (e.g., Donner 2007, Brotzge and Donner 2013, Ripberger et al. 2015,

2020). In efforts to make weather warnings more conducive to taking action, in 2014 the

NWS implemented Impact-based Warnings (IBWs) wherein SVR and Tornado Warnings

can include a tag detailing expected impacts to people and/or property. Research has

shown that including IBWs increase one's probability of taking actions such as sheltering in

place or seeking safer shelter (Ripberger et al. 2015, Casteel 2016), but again, no study exists that focuses on severe hail. Experiments are also ongoing to incorporate Probabilistic Hazard Information (PHI) into weather warnings, which will provide the likelihood of the hazard occurring. The work presented here solicits feedback of farmers' and ranchers' perceptions of hail risks and needs for hail warning messages, which can guide NWS in making SVR and PHI language for hail more effective and meaningful to the agricultural community.

To review, this study is innovative for its emphasis on hailstorm perceptions within the agricultural sector. While we seek a broad spectrum of information, two main research questions can be established: (a) How do farmers and ranchers perceive the severity of hailstorms and their vulnerability from them, and what factors drive these perceptions? and (b) How do farmers and ranchers receive and respond to warning messages for severe hail? By focusing on the small domain of eastern Colorado, local forecasters and other decision-makers can better understand the needs of the agricultural communities they serve, and thus foster stronger relationships, as opposed to assuming that more general perceptions apply in their localized areas. Moreover, this study paves the way for future work that can employ similar methods with farmers in other parts of the country that experience hailstorms under different meteorological regimes and primary crop production to see if similar themes emerge.

B. Theoretical foundations

The semi-structured interviews were developed in such a way as to elicit the mental models of the agricultural stakeholders about hailstorm risks. A mental model can be thought of as a set of relevant beliefs and inferences that someone has regarding a risk

which in turn guides his or her perceptions of and responses to it (Bostrom et al. 1992, Morgan et al. 1992, 2002). The mental models approach has been utilized in numerous disciplines for decades (Morgan et al. 2002 and references therein). It has proved insightful for studying natural hazards risks, for example, understanding public perceptions of flash floods (Wagner 2007, Morss et al. 2015, Lazrus et al. 2016), hurricanes (Bostrom et al. 2016), heat waves (Chowdhury et al. 2012), wildland fires (Zaksek and Arvai 2004), and climate change (Bostrom et al. 1994, Otto-Banaszak et al. 2011).

One strategy to explore a person's mental model is to begin the interview by allowing the respondent to freely address broad, open-ended statements about the topic at hand (Morgan et al. 2002). As such, the interview for this study was designed to begin with an invitation for the interviewee to respond openly to the statement, "Tell me about hailstorms (in eastern Colorado)," thereby revealing initial, unprimed beliefs and emotions associated with hailstorms. The interview process to further elicit people's mental models can draw from different theoretical frameworks that are relevant to the hazard context and research questions of interest. Based on our interests in studying farmers' and ranchers' views about forecast and warning messages for hail as well as perceptions of hail risk itself, we drew upon the Protective Action Decision Model (PADM) in designing the interview protocol. The PADM (Lindell and Perry 2012) is an integrated framework that draws on concepts and theories from the hazards, risk, and judgment and decision-making fields in order to characterize the components and processes by which people are made aware of, assess, and respond to environmental hazards. Per the PADM, environmental cues and warning messages about a hazard are received and interpreted by someone. Subsequently, people's perceptions of the risk, of protective actions they can take, and of social

stakeholders (including government authorities and media groups) influence the their

behavioral response to the risk. Accordingly, the PADM provides a structure for eliciting

people's mental models of how they perceive, interpret, and respond to hailstorm risks.

The interview protocol begins with perceptions of how farmers and ranchers perceive their

exposure and sensitivity to hailstorms (Q9-14). Interviewees are later asked to provide

environmental cues and information channels used to deduce a hail threat (Q18,19,25),

comment on the efficiency and accuracy of warning messages (Q20,21), and convey

emotional and behavioral responses to the message (Q23,24). Consistent with the PADM,

warning message effectiveness has been shown to be of great importance in determining

public action in response to a threat (Trumbo 2013, Morss et al. 2015, Carr et al. 2016,

Lazrus et al. 2016). As such, Q21 and Q22 of the interview protocol appeal to the utility of

SVR as they are currently operationalized, by seeking input on the risk information most

critical to farmers and ranchers about an impending hailstorm.

The constructs of vulnerability and risk in the natural hazards domain are defined in

many ways, and their relationships to each other can also take on a number of

mathematical and conceptual forms depending on the research objectives and field of study

(Turner et al. 2003, Cutter et al. 2008, Cutter and Finch 2008, Paul 2011, Wisner et al. 2012,

Zarafshani et al. 2016). Here, we follow Wisner et al. (2012) in defining overall *risk* as the

intersection of *hazard* and *vulnerability.* Applying this framework to the study here, the

hazard is a hailstorm; not only are we interested in the occurrence of a hailstorm but also

its *severity*, or the degree of negative impacts. In this way, we consider severity more

broadly than, but including, the NWS's severe hailstone size. Vulnerability can be

partitioned into components of *exposure* (i.e., a person experiencing hailstorms on his or

her property) and *sensitivity* (i.e., the social, economic, and demographic characteristics that influence the degree to which one is affected [Cutter 1996, Cutter et al. 2000, Turner et al. 2003, Smit and Wandel 2006]).

C. Methodology

Participants were recruited through purposive and convenient sampling, stemming from initial organizational contacts and then expanded via snowball sampling (Patton 2002). Recruitment language was developed that explained the study purpose, invited agriculturists to participate, and contained a link to a Google Form on which interested parties could sign up to participate. In Spring 2019, the recruitment language was sent to extension agents in 26 counties across eastern Colorado, along with the Colorado Corn Growers Association, Colorado Wheat Growers Association, USDA Agricultural Research Service, and the NWS. These organizations disseminated the information either directly to farmers on their contact lists, via social media, or newsletters. In addition, the Colorado Climate Center, which oversees the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), forwarded the study invitation to members who had submitted at least two hail reports in the past five years. A few participants were also recruited in-person at an annual wheat field day in Akron, CO. All farmers and ranchers who expressed interest were contacted, and interviews were arranged.

Two interview pretests, one with a graduate student at Colorado State University and one with a farmer, were conducted to assess interview timing and content. Minor adjustments were made to the interview protocol after the farmer's pretest, but the success of this interview allowed for it to be retained in the sample. A total of 15 interviews were

conducted from June-August 2019, 14 of which were in-person and 1 was via telephone. The average interview length was 28 min (range 18 to 47 min), and interviews took place either in a home, place of work, or a local restaurant.

The sample of participants were concentrated spatially in the northeastern part of the eastern Colorado but spanned throughout the area (Fig. 5.1). The interviewees represent a wide range of farming experience within eastern Colorado (3-73 years), with the majority having farmed in the area for at least 20 years (Table 5.1). The sample also included a mix of small and large farmers, from a 3-acre vegetable farmer to operations exceeding tens of thousands of acres. The most frequent crops farmed were wheat and corn (7 each), while vegetables, millets, sorghum, and sunflowers were also each grown by at least three people (Table 5.2). This is representative of the distribution of eastern Colorado crops as reported by the USDA in 2018, with wheat, corn, and sorghum the top three crops planted by acreage. Five interviewees reported raising cattle, the highest number of any livestock. One-third of the respondents were CoCoRaHS observers, and nearly half had filed a crop insurance claim due to hail damage within the last two years (Table 5.1), but these were not distinguishing factors in participants' responses.

To assess the interviewees' mental models surrounding hailstorm risks and vulnerabilities, each interview began with the statement "Tell me about hailstorms (in eastern Colorado)." The interview protocol was then divided into five main sections. Interviewees first were asked about the effects of hailstorms on personal and career livelihoods. The second section focused on hailstorm risks and severity by probing farmers and ranchers for the most serious negative impacts associated with hailstorms.
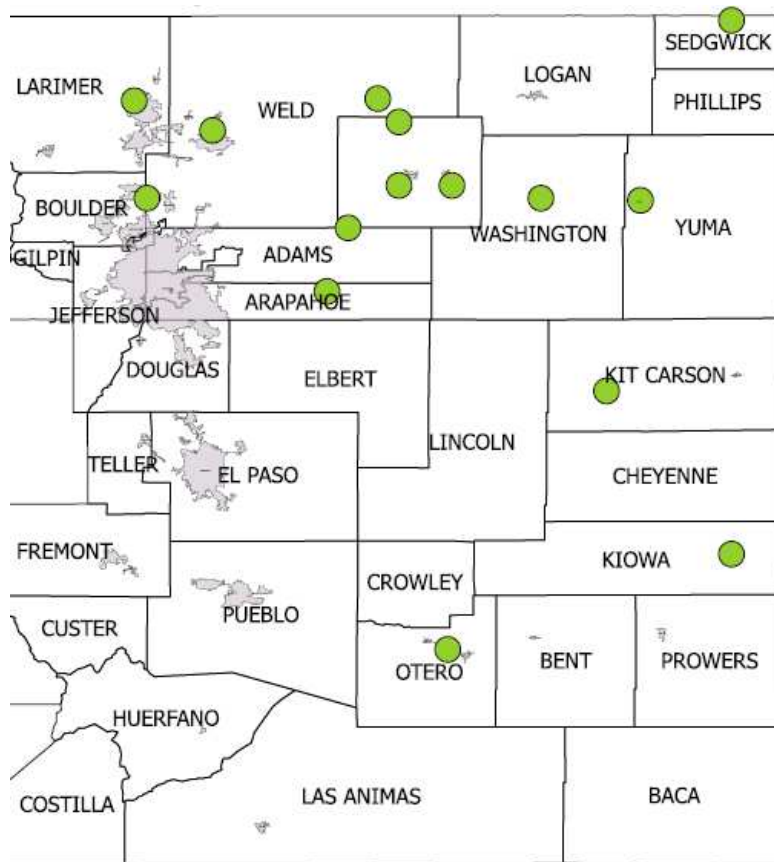
Fig. 5.1: Approximate locations of interviews. Urban areas (shaded) and county names are also shown for reference.

Table 5.1: Demographic characteristics of fifteen interviewees.

Statistic	Responses
Years farmed in eastern Colorado	3 – 73 years (median 28 years)
Years farmed overall	11 – 73 years (median 32 years)
Acres currently farming	3 – 50,000 acres (median 1400 acres)
CoCoRAHS Hail Observer?	
Yes	5
No	10
Crop insurance claim filed in past two years?	
Yes	7
No	8

Table 5.2: Distribution of primary crops and/or livestock raised by participants. Most participants listed more than one crop or animal, which is reflected in the counts.

Crop / Livestock	Count
Corn	7
Wheat	7
Cattle	5
Millets	4
Sorghum / Milo	4
Vegetables / Fruits	4
Sunflowers	3
Chickens	2
Hay / Pasture	2
Cereal Rye, Sheep, Horses, Alfalfa, Hemp, Triticale	1

Interviewees were also asked when they considered a hailstorm to be "severe," for comparison with the NWS definition which is currently based solely on maximum hailstone size and does not include characteristics such as duration, volume, or accompanying wind speed. Interviewees specifically commented on two scenarios for comparison, namely (a) a hailstorm that produces a lot of small hail that accumulates to appreciable depth and (b) a hailstorm that produces a few very large hailstones in excess of baseball size, both of which are common in eastern Colorado but can have different effects on a field of crops. The third section of the interview gauged perceptions of vulnerability to hailstorms. The exposure component was measured by asking interviewees to provide a 1-to-10 rating of how likely they perceived severe hail to occur on their property during a given year (according to their definition of "severe"), and sensitivity was assessed through a 1-to-10 rating of how sensitive they perceived themselves to be toward the effects of hailstorms (using the

definition of sensitivity given in Section A). This rating scale style is preferred for its simple

interpretation and ease of performing statistics such as mean and median. Each

respondent was also asked to comment on any perceived changes in exposure or

sensitivity over time, as well as changes in other hail characteristics such as size and season

length. The fourth section of the interview protocol drew on PADM to investigate hail risk

messaging and responses. Interviewees were asked to give their preferred channels of hail

forecasts and warning messages, perceptions of the accuracy and contents of warning

messages, affective responses, and any stimulated real-time action steps. The final

interview section sought input on future mitigation strategies to combat the impacts of

hailstorms and also inquired about crop insurance influences on perceived risks and

vulnerabilities. Each interviewee was given an opportunity to share any closing thoughts,

and then the interview concluded. Prompts such as "Tell me more about" or "Can you

elaborate?" were used to encourage participants to explain their thinking as much as

possible. For their time, each interviewee was given a small gift courtesy of CoCoRaHS.

The complete interview protocol, which contains 29 questions and a short demographic

questionnaire, can be found in Appendix A.

Interviews were transcribed by Kelsey Transcripts and inductively analyzed using

NVivo Pro version 12. The reflexive thematic analysis procedure (Braun and Clarke 2006,

2019; Terry et al. 2017) was followed to create common themes among the interviews.

This approach allows for transcripts to "speak for themselves," with themes developed as

transcripts are coded rather than determined *a priori*. Thematic analysis has been used in

other studies within the atmospheric sciences that apply social science methods to better

understand risks from tornadoes, hurricanes, and flash floods (Demeritt et al. 2010;

Demuth et al. 2012, 2020; Ash 2017). Here, 75 unique codes were generated, and they were subsequently combined, defined, and grouped under five preliminary categories following the interview structure. The codes within each category were consolidated into common themes, some of which overlapped into other categories. A final synthesis narrowed the focus to two overarching categories: (a) vulnerability and severity, which represent two leading factors of overall hazard risk, and (b) forecast and warning messaging, which serve to assess reception and response to impending risk. The thematic analysis was cross-checked by a co-author and social science expert, with mutual agreement reached. Given the sampling approach, the results presented herein cannot be generalized to the entire agricultural sector of eastern Colorado, yet the sample is adequate to gain valuable insights (Braun et al. 2018). In the following discussion, interviewees are referred to as "Interviewee #1," and so forth to protect personal information.

D. Risk Assessment: Vulnerability and Hazard Severity

To better understand how eastern Colorado farmers and ranchers deal with the effects of hailstorms and thereby reveal strategies for potential improvements in risk communication, it is of worth to investigate the aspects of exposure, sensitivity, and severity.

1. Exposure – Life in "Hail Alley"

Perhaps the most prevailing assertion of all interviewees is that eastern Colorado is a hot spot for hailstorms, to the point where farmers and ranchers assume they will be impacted by at least one hail event each year. As Interviewee #4 said, "this is just part of Colorado and it's always been a part of Colorado," and Interviewee #11 stated bluntly, "In this country, it's gonna hail somewhere, and it's gonna be severe somewhere." References

were made to Colorado lying within "Hail Alley," and Interviewee #11 referred to the area as the "hail capital of the United States." Some interviewees even associated hailstorms with specific towns or creeks along which they seem to travel, and one interviewee correctly stated that Colorado was the leading state for hail claims in 2018 (State Farm 2019). While most farmers and ranchers did not posit a theory for the area's propensity for hailstorms, moisture patterns and the mountainous terrain were seen as local factors influencing hail events. The perception of hail as a common nuisance in eastern Colorado is consistent with meteorological data (Allen and Tippett 2015, Childs and Schumacher 2019).

When asked to give a 1-to-10 rating of perceived exposure to severe hailstorms occurring on his or her property on any given year, a bimodal distribution resulted, with a mean response of 5 (Fig. 5.2a). In other words, while agriculturalists perceive hailstorms as ubiquitous across eastern Colorado, they tend to deduce either a very low or very high chance of severe hail occurring on their property. One explanation given for this wide range of perceived exposure is the spatially localized nature of hailstorms. Interviewee #1 shared that ". . . it's so localized. You're driving down the road and you see this swath and it looks like somebody took a shotgun to the plants. And then you drive another half a mile down the road and nothing . . . or very little damage."

A common thread emerged of a steady long-term state of damaging hail events but a recent increase in their occurrence. Several historical references, as early as the 1940s, were given as evidence for the perceived long-term record of major hailstorms. Interviewee #5 recalled a particularly memorable hail event from the 1960s in which she rode through "ice bergs" of hail on her horse to search for a man who had been caught up in

floodwaters generated from "five to six hours of continuous hail." In addition to their

personal experiences, several interviewees recalled how their ancestors also dealt with

hailstorms or told them about harrowing experiences, which both affirms the strong

familial ties often present in agriculture as well as the resonance of major hailstorms on

their livelihoods. Others called upon their life experiences more generally, such as

Interviewee #13 who stated, "It's always been that way," and Interviewee #11 who said,

"It'll always be that way. Nothing's going to change or has changed that I can see," in

contrast to the more common notion of a recent increase in events. To some, repeated

cycles in hail occurrence lead to an overall steady long-term state. Interviewee #4 said,

"You always [figure] you're going to have one bad year out of every seven years."

Interviewee #7 had a very similar take, asserting that "if you've gone . . . six, seven years,

[then] you're kind of thinking you're due." The cyclical nature of hailstorms seems to

interviewees to be linked to moisture patterns, as Interviewee #9 indicated, "The old adage

here is . . . if it's dry weather, you don't get rain [and] you don't get hail . . . a wetter type

scenario, more moisture, higher chance of hail."

In contrast to the perceived long-term trend, the majority of interviewees were

quick to express the recent uptick in damaging hail events, spanning the temporal range

from "this year (i.e., 2019; Interviewee #2)" to "in the last decade (Interviewee #9)." Five

interviewees made reference to the record-breaking 2018 hail season, which saw an

unprecedented number of very large hailstones reported (Childs and Schumacher 2019).

Interviewee #4 summarized the 2018 season succinctly:
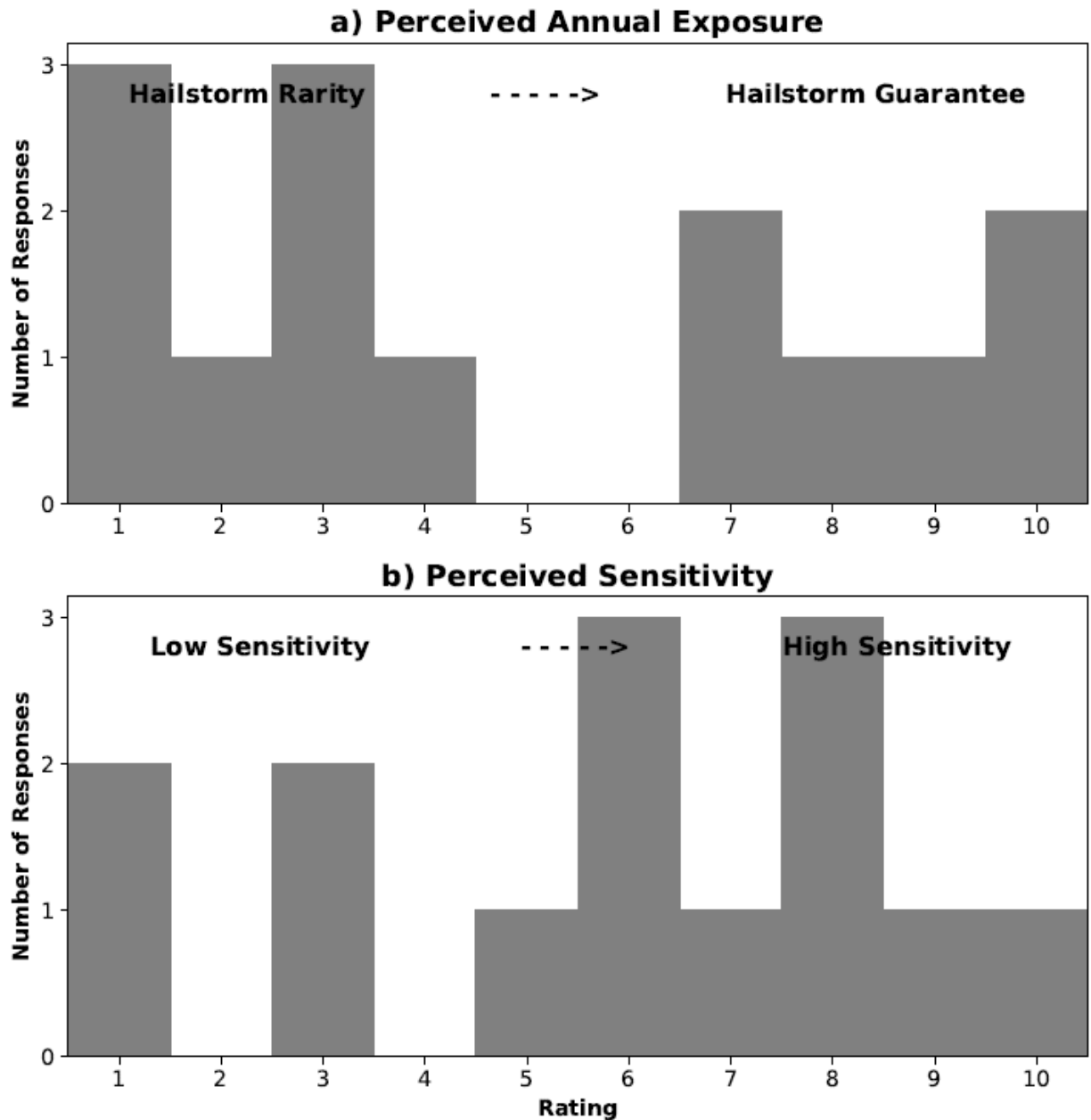
Fig. 5.2: Histograms of ratings of (a) perceived exposure to hailstorms on a given year, and (b) perceived sensitivity to hailstorms among the interview sample.

then 2018 last year, it was up and down the entire Front Range. That one I would say . . . was very different. You never hear about everybody getting it – like, Colorado Springs got it multiple times. Our insurance adjuster for the crops visited us multiple times in 2018, and she had two roofs put on her house from hail . . .

within about a three-month span. [Y]ou had Colorado Springs where those animals were killed and . . . the Cheyenne [Mountain] Zoo; you had [it] in Denver, you had it up along the Front Range like Fort Collins . . . and then we got it [here] on June 19th. That was grapefruit-sized — we lost 70 percent of everything that was planted. And then up here, we got clipped on July 27th. So I would say 2018 is definitely an asterisk, like 'What the heck was that?'

In addition to the severe 2018 hail season, observational data affirms an increase in both severe hail reports and severe hail days across eastern Colorado since 1997, with the latter metric notable for its lesser influence of population bias (Childs and Schumacher 2019). While it remains to be seen if the trends will continue, several interviewees hinted that ongoing climate change may result in more frequent extreme events such as hailstorms, another assertion that has support from modeling studies (Brimelow et al. 2017, Rasmussen et al. 2017, Trapp et al. 2019). The influence of climate change on human perceptions of hailstorms is beyond the scope of this assessment but worthy of future investigation.

2. Sensitivity – The growing costs of hail events

As with exposure, interviewees were asked to give a 1-to-10 rating of their perceived sensitivity to hailstorms and whether that number had changed over time (Fig. 5.2b). With most ratings between 6 and 8, and only four ratings in the lower half of the scale, most farmers and ranchers consider themselves more sensitive to hailstorms than not. Of greater interest, however, is the common theme of increasing sensitivity over time, indicating the ability to deal with the effects of hailstorms is becoming more difficult. Most interviewees attributed their perceptions of sensitivity either to market trends or the type of crops they plant. Interviewee #12 explained how in response to the boom of the early 2010s decade when wheat and corn were sold for $9 or $10 per bushel, "everybody raised

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their prices, but as soon as commodities dropped to half, all your input suppliers and machinery dealers did not lower their prices," thus putting a financial strain on the farmer. The recent years of low commodity prices was also expressed as "using up our war chest (Interviewee #9)," that meant smaller cash reserves to use in the case of unforeseen costs from hailstorms.

Aside from the market, the type of crop grown can determine one's sensitivity. Considering the two most prevalent crops, interviewees perceive wheat as more susceptible to hail damage than corn due to its smaller seeds and heads. Interviewee #10 considered himself

> more highly at risk because of wheat being our primary crop. If we had a rotation of some spring crops, we'd have a little bit less risk probably, but even those crops that have some risk, [like] corn and sorghum . . . have some fairly significant damage as well, although they might be able to come back a little bit better than wheat.

Specialty crop and vegetable farmers have amplified sensitivity due to the public tendency to purchase only the most pristine-looking or trendy vegetables. As Interviewee #3 humorously said, "You get hail through Swiss chard and it's literally Swiss chard. You get hail through heads of lettuce and it's turning brown and the edges are all black a couple days later. You cannot market it." Interviewee #4 expressed concern that if "one hailstone . . . bumps [a watermelon], it immediately starts a rotting process internally." Sensitivity is also dependent on when hailstorms occur during the growing season. In spring, when most crops have just been planted or are yet to mature, farmers have a greater chance of bouncing back from a hailstorm. However, hailstorms during June and July preceding the wheat harvest are particularly concerning since by this time the heads have developed and are prone to being stripped by an intense storm. As will be seen, the variable crop impacts from hailstorms have some agriculturalists considering alternative planting strategies in

the future. Perhaps Interviewee #3 summarized the aspects of sensitivity best with the statement, "I don't think our risk [i.e., sensitivity] has changed; I think the likelihood of that risk actually coming to fruition has changed." In other words, meteorological and non-meteorological factors alike are leading to a more frequent realization of the potential negative impacts from hailstorms.

3. Severity – Does size truly matter?

When asked to provide their stipulations for a hailstorm to acquire a "severe" designation, some interviewees gave a specific size threshold and others discussed the nature or the impacts of the hailfall. A common theme emerged that small (i.e., less than 25.4-mm) hail, either in large volumes or wind-driven, contributes most to crop losses, whereas very large hailstones (e.g., at least 50.8 mm) are most damaging to physical structures. Interviewee #15 spoke to the wind effect:

> The ones that have the winds with them . . . are the ones that seem like they do the most damage. [It] can be smaller hail, the size of a dime or pea-sized but boy, if the wind there is with it, it destroys things fast. You can have bigger ones that . . . come straight down, and they don't do near the damage.

Interviewee #6 said, "It's not necessarily the size of the stone that matters. It's the amount of them and how hard they are . . . [Large hailstones are] probably the ones that hurt that roofs, but the crop damage is caused by not necessarily size of stone but volume of hail." Interviewee #6 also articulated a positive correlation between the duration of hailfall and damage: "Most of the time, the most severe damage that we see is when you have a lot of marble-sized hail [that] lasts for more than just a few minutes."

That volume and wind speed are commonly associated with perceived hailstorm severity affirms the agriculturalist's focus on characteristics producing the greatest crop

damage. Indeed, when asked to identify the most serious risks (defined in context as a

negative effects) of hailstorms, thirteen interviewees specifically mentioned crop loss, and

ten mentioned financial impacts (Fig. 5.3). Physical damage received the second most

responses, but was almost always mentioned after crop loss. Two interviewees referred to

hail as "the great white harvester" that can decimate an entire field of crops. The

consequences of losing crops to hail goes far beyond the field, however. For

agriculturalists, crop yield equals monetary gain, so hailstorms can literally strip a farmer

from an income source. This paradigm was summarized by Interviewee #6 who said the

most serious risk from hailstorms was "the crop loss . . . it's millions of dollars."

Furthermore, the trickle-down effects from hailstorms can be far-reaching and have
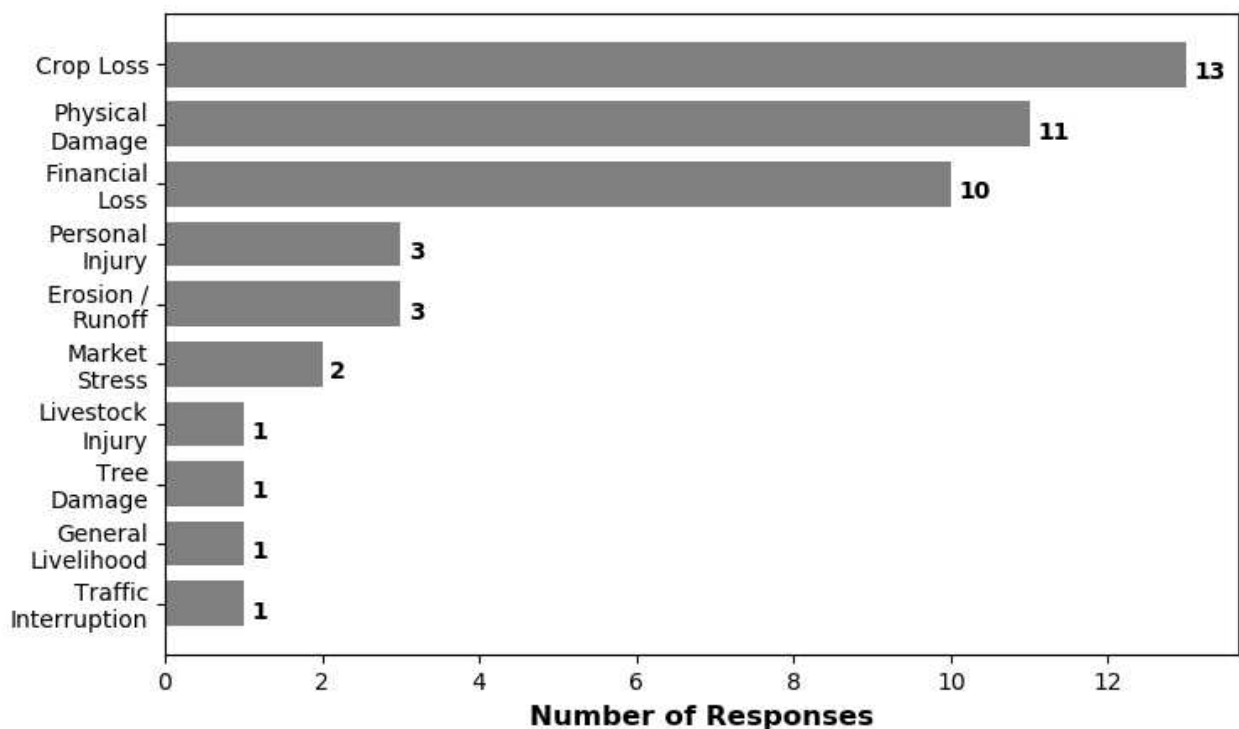
Fig. 5.3: Frequency distribution of responses to "What are the most serious risks associated with hailstorms in eastern Colorado?"

significant impact on the farmer's and community's livelihoods. Most agriculturalists have

a number of market streams for their crops and livestock, and removing just one of these

pathways from losses due to hail can be devastating. Interviewee #7 related a typical hail

loss scenario:

> So in years when things are bad in the agricultural community, tire shops layoff. The tire shop [owner] – his wife doesn't get her hair done . . . so the beauty parlor sees a dip. [And] it trickles down to grocery stores each time. [T]hey talk about the ag[ricultural] dollar rolls in seven times in a community, so you take that dollar out – seven bucks out of the community – it's a severe adverse effect to agriculture communities, not only the farmer.

Interviewee #8 also articulated the trickle-down effect that can ensue from losing a wheat

crop:

> Well, we lost all this wheat. Well, that also means that's less wheat to go for the cattle. That's less wheat to go for the hogs. It's less wheat to go for bread and all this other stuff. And, if an entire area is wiped out of wheat or corn or whatever the case may be, that has to be absorbed somewhere. And usually it's at the grocery store, and people who spend are like, 'Why are the prices so high?'

Interviewee #8 concluded that "the entire community depends on farming and ranching."

Indeed, the rural communities of eastern Colorado are small and close-knit, so the local

farmer is often well-known and seen as an integral part of the community's well-being. As

anecdotal evidence, during one interview at a mini-mart in a small town with only a

handful of businesses, the local fire marshal and a shopkeeper came in to buy lunch and

proceeded to exchange friendly banter with the interviewee, signaling his familiarity and

respect within the community. At another interview that was held at a rural diner and

livestock arena, a previous interviewee from a town more than 30 miles away was seen

eating breakfast and turned out to know the current interviewee. Since these rural

communities are close-knit and dependent on local agricultural output, any crop losses

from hailstorms are quickly absorbed by the residents. Cutter et al. (2016) plotted six

components of rural resilience and found that the eastern Plains of Colorado have their lowest resiliency in the environmental and community capital categories, affirming the toll natural disasters can have on agricultural production and the local economy. A secondary trickle-down effect mentioned by multiple interviewees starts with soil erosion as hail that strips a field bare eventually melts and take the soil away with it as runoff. This can render the field unplantable for the following year, as the nutrients and matter necessary for crop growth are removed. Even if a field of crops is not entirely decimated, crops that are impacted by hailstones become susceptible to bacteria that can affect yield productivity.

E. Risk Communication: Forecast and Warning Messages

Given that hailstorms are a perceived threat to eastern Colorado farmers and ranchers each year, it is worth investigating how the various components of forecast and particularly short-term warning messages are utilized and perceived by this sector.

1. Sources and channels – An eye to the sky

Weather is an integral part of the farming lifestyle, and as such many farmers and ranchers are avid weather watchers and stay engaged with impending weather threats. For the majority of interviewees, the most effective tool for ascertaining a potential hailstorm threat is to assess the surrounding environmental conditions and sky features, one of the factors that initiates the PADM process. Several respondents mentioned that a warm, humid, moisture-rich atmosphere is an omen. On shorter time scales, a sudden temperature drop, deep, dark clouds, strange animal activity, and noisy clatter are used by many interviewees as alerts for hail. Over half of the interviewees specifically mentioned a greenish hue to the clouds or sky in advance of a hailstorm. For example, Interviewee #14

said that "if we see a green cloud up in there somewhere . . . it's amazing as a [hail] predictor," and Interviewee #8 mentioned that from "years of experience, if it's got a greenish tint, it's most likely it's going to have some hail in it."

Table 5.3 displays the frequency of typical channels of severe hail warnings used by the interviewees, with the highest count for each source in bold face. Television, online websites, and NOAA Weather Radios are rarely or never utilized by most farmers and ranchers. Alerts from family members sometimes reach the interviewees, and by far the most utilized channel for hail warning messages is the cell phone, either via the Emergency Alert System (EAS), county-level warning systems such as Code Red, or private-sector weather applications. Most interviewees cited the availability of their phones compared to other channels, particularly when they are working outside and not around a computer or television. Of the apps utilized among the sample, NWS apps were the most popular, with The Weather Channel, Wunderground, Weather Bug, and Storm Radar each being used by at least three interviewees (Fig. 5.4). Radar displays are often used by the interviewees to verify warnings and see where the warned hailstorm is specifically located. Interviewee #15 even said that when storms are developing, "the first thing I do is go to my radar app on my phone and look to see what the colors are . . . for that cell that is coming [my] direction," and Interviewee #8 added that "based on the reflectivity, I can get a better idea of what is going on."

Table 5.3: Participant responses to their preferred sources of receiving warning messages for severe hail. Results are displayed from most to least frequent 'Always' response.

How regularly do you receive warning messages for severe hail from the following sources?					
	Always	*Most of the Time*	*Sometimes*	*Rarely*	*Never*
Phone Alert (EAS, Apps)	**7**	**4**	3	0	1
Internet	3	1	2	4	**5**
NOAA Weather Radio	2	1	2	1	**9**
Friends or Family	1	3	**6**	3	2
Television	0	4	1	4	**6**
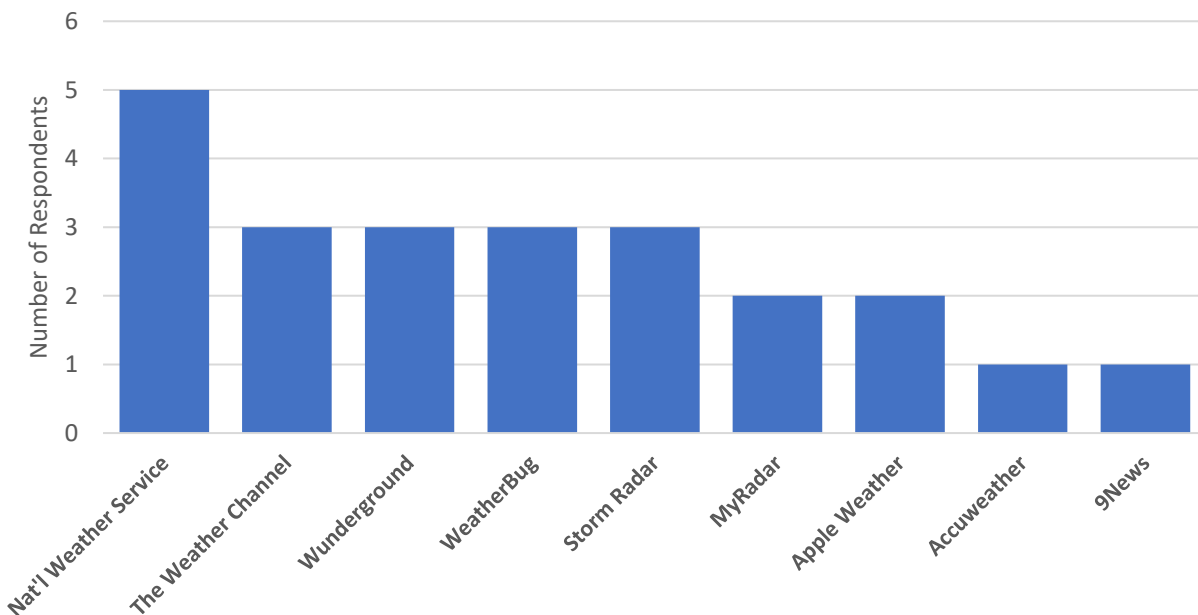
Fig. 5.4: Frequency of phone applications used by the interview sample when receiving an alert for severe hail.

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2. Perceived accuracy – Predictability at a premium

The SPC issues probabilistic convective outlooks for severe hail each day and general severe probabilities up to eight days in advance, and severe weather watches issued by SPC are generally in effect out to six hours. While these metrics are helpful, more precise short-term prediction of the path and severity of individual hailstorms is the subject of ongoing research efforts, such as machine learning techniques (Gagne et al. 2019), development of the HAILCAST model (Adams-Selin and Ziegler 2016), and the NWS Warn-on-Forecast initiative (Stensrud et al. 2009), to name a few. When asked to assess the accuracy of hail warnings, the interview sample confirmed the difficulty of short-term prediction. A common sentiment was that warnings are spatially accurate within about a county-wide radius, but as Interviewee #10 remarked, "whether it hits you or not is another story." The size of hail to be expected is also perceived as hard to predict; as Interviewee #14 stated, "it could be three inches of pea sized or it could be a spattering of golf ball size." Despite the forecasting challenges, Interviewee #12 believes that forecasters "do the best with what they can," and Interviewee #5 said "all they can do is say 'mild' or 'moderate to severe.'" Agriculturalists perceive warnings that are verified by trained spotters or storm chasers as providing more accurate size estimates, and radar-indicated warnings are perceived to overestimate actual hail size. In fact, there are documented limitations in using hail size algorithms from Doppler radar parameters that tend to overestimate hailstone sizes (Cintineo et al. 2012, Ortega et al. 2016). When asked to provide the single most desired piece of information related to a coming hailstorm, the majority of respondents wanted to know, as Interviewee #10 put it, "whether it's coming right at me." The ability to pinpoint the exact path of the hailstorm would surely help

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farmers know whether action steps need to be taken to protect life and property, but the rural eastern Plains of Colorado complicate location-based warnings because of the scarcity of towns and roads used as reference points in the warning message, as well as the relatively large area within a small town's jurisdiction. Interviewee #14 drew on a recent personal experience wherein a warning for severe hail was associated with a town that was 25 miles to the north and yet the interviewee's home also had that town as its address. "It would be more accurate to the locals . . . and to our families" to have more pertinent geographical information in the warnings, Interviewee #14 concluded. This desire for more personal-scale information is a common theme in risk communication of hazards (Nagele and Trainor 2012, Morss et al. 2016, Childs and Schumacher 2018a).

3. Affective responses – 'Here we go again'

The behavioral responses to a risk communication message, including those related to natural hazards, are often partially influenced by affect and emotions (e.g., Slovic et al. 2004, Lindell and Perry 2012, Demuth et al. 2018), which can be triggered by a variety of factors. For the interview sample, affective responses generally fell into one of three camps. First, words such as "nervous," "anxious," "ill-at-ease," "frightening," and "apprehension" conveyed a sense of anxiety and fear at the prospect of a hailstorm and its potential financial losses. Interviewee #8 commented, "It causes a lot of stress . . . and it really is something that everybody worries about." A second common response was that of acceptance. As Interviewee #11 put it, "If it happens, it happens. Nothing you can do about it [except] accept it." This feeling is tied to the concept of lack of efficacy (Lindell and Perry 2012), wherein the person feels unable to do something in the face of an event. A perceived lack of self-efficacy led to some interviewees relinquishing control to the natural

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world, such as Interviewee #13 who stated, "You can't do anything about it. That's Mother Nature." Others spoke of a supernatural authority governing the weather, such as Interviewee #7 who said "You're just at the mercy of God," or Interviewee #11 who said of hailstorms, "It doesn't bother me. That's God's business – He can take care of that." Indeed, although attribution of natural hazards and disasters have trended away from 'acts of God' and toward 'acts of nature' in recent decades, it has been shown that one's spiritual beliefs can and still do affect his or her risk perceptions of the hazard (Slimak and Dietz 2006, Sherry and Curtis 2017). Perhaps the most heartfelt emotion experienced by farmers and ranchers upon hearing a threat for severe hail is that of dejection or sadness. This response is primarily sourced from the hard-working farming lifestyle, which prides itself on raising and providing food for the country's citizens. When that is taken away by a hailstorm, one is left feeling defeated. Interviewee #9's comments exemplify this mindset: "We're all here for a reason, and part of that reason is the gratification of our hard work . . . there's a hole in your psyche that takes a while to fill back up with something else." Feelings of dejection are amplified when losses from a hail event mean fewer financial resources for other critical farming expenses. Again, Interviewee #9 sheds light on this idea through a personal experience:

> Well, I can remember last summer . . . you go through the planting process and the crop's coming and it's looking nice, so then your mind starts thinking about . . . we got to get the combine tuned up, do I need any parts for that or . . . grain bins cleaned out, do we need a new [one of these] . . . your mind starts getting down that [path] and then within three days, that's all moot, [and] now your mind changes into 'Can't buy this, can't buy that' because now I have a finite amount of money and [have] to stay within the confines of that . . . so it puts a lot of pressures on you.

Interviewee #4 expressed that in agriculture, "there's always a need [for] a new tractor, a new truck, or . . . taking the next step that every business wants to take." When hail

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recovery mandates postponing such upgrades, the farmer or rancher is met with deflated hopes.

4. Protective action – Nothing you can do for the crops

After a warning message has been received and processed by the farmer or rancher, he or she must decide what behavioral responses to make in order to mitigate negative impacts. Unsurprisingly, the interview sample agreed that, as stated succinctly by Interviewee #15, "there's really not much you can do." For large-scale operations, covering crops or herding livestock into barns is not feasible. Interviewee #12 joked that perhaps one day there would be "a force field that you could bring up over your farm," but until that comes to fruition, crops and animals are largely on their own. Smaller vegetable farmers mentioned spreading protective tarps or nets over their vegetables, but large hail can still penetrate through these devices. The most tangible action step that is routinely taken upon receipt of a warning for severe hail is to protect people and physical property. Alerting family or workers, moving vehicles and equipment under shelter, and closing windows were repeatedly mentioned as practical protective measures.

Given the inability to hail-proof crops or rangeland, respondents were not overly enthusiastic about implementing adaptive strategies to protect against future hailstorms. A few smaller farmers mentioned changing roofing materials or building additional greenhouses to protect specialty crops from hail, while larger farmers tended to suggest crop diversification and rotation to reduce losses. As Interviewee #14 put it, "we're gonna have to find substitute crops here if we're going to stay around." Some interviewees mentioned adding sorghum or millets to their crop rotation because of the relative resiliency of their residue compared to other crops, which would allow a field destroyed by

hail to be planted the following year. Interviewee #3 was a big proponent of increasing

organic matter in the soils as a buffer against hail impacts: "Building soil organic matter

and appropriate level of nutrients and biomass and microbacteria . . . all the soil health

practices really aid in plant recovery time." Similarly, Interviewee #9 sees "regenerative

value, cover crops, living roots, [and] soil biology" as "vehicle[s] to continue increasing

organic matter and building resilience" against hail and other natural hazards. For all that

can and cannot be done to mitigate the negative effects of hail, the idea of perseverance was

on interviewees' minds. As Interviewee #5 concluded, "You just go on with your life."

F. Application and Recommendations

In light of the knowledge gained from the interviews, a few recommendations and

directions for future work are offered. First, research efforts are encouraged in the

predictability and prediction of hail volume, duration, and wind effects. The current NWS

SVR framework only warns for hail in excess of 25.4 mm and does not contain estimates of

any other hail characteristics. Moreover, the upward adjustment of the severe threshold in

2010 by the NWS was motivated by suggestions from emergency management and media

partners and was believed to better capture the threshold for significant hail damage (NWS

2010). However, the interviews with eastern Colorado farmers and ranchers suggest that

small hail, either in large quantities or wind-driven, is of great concern for crops and the

livelihoods of those who grow them. Therefore, having forecasts or warnings for smaller

hail that is accompanied by wind or is of substantial duration, would greatly benefit the

agricultural community. Given the recent accumulating hail events along the Front Range

urban corridor, those who live in these areas would also benefit from advanced warning of

small-hail-large-volume situations. Toward this end, continued research that identifies

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environmental conditions favoring high-volume or wind-driven hail events through modeling or machine learning techniques is recommended.

Many interviewees expressed a sentiment that the agricultural impacts of hail should be recognized and acknowledged more broadly. In the words of Interviewee #8,

> I see hail as something that needs to be a little more recognized. I know that when it happens in the cities it's a bigger deal because there's more personal property damaged. But people don't see the crops as a big deal even though maybe one crop costs more money in insurance than all the cars on a city block [that] are damaged . . . People don't stop to realize the long-term effects of that.

Even new farmers can be unsuspecting of the consequences of hailstorms. Interviewee #4 stated that "you get a lot of people come to Colorado, they love Colorado, they love the outdoors, they want to get reconnected with nature so they start the farming, and they just don't have any idea . . . Colorado will punish you." While the agricultural community is highly influenced by the weather, it is possible that their needs are not being met by the weather forecasting community relative to the impacts they face. Interviewee #14 expressed a desire for "the weather people . . . to be more relative to the agricultural community," and Interviewee #4 feels that "news is more focused on [the] Denver area." Facilitating stronger relationships between the weather and agricultural sectors could help farmers feel more appreciated and also express their weather and forecasting needs, such as those revealed in this study. One platform to potentially promote this relationship is with Impact-Based Decision Support Services (IDSS; NWS 2018, Uccellini and Ten Hoeve 2019), whereby NWS provides critical weather information to their partners and constituents. In addition, Integrated Warning Teams (IWTs; Morris et al. 2008) that aim to improve weather messaging could benefit from including representatives or seeking input from the agricultural sector. Building these relationships can also help farmers establish

trust in the weather community, a quality which has been shown to promote greater behavioral response to warning messages (Sherman-Morris 2005). As such, future work by the authors will take the findings gleaned from this study to forecasters and aim to better understand the path toward improvements in severe hail risk communication.

In terms of mitigating the negative impacts from hail, continued efforts are recommended to find more sustainable and resilient soils and make crop residue more accessory to future field fertility. There is no indication of a downward trend in damaging hail events across eastern Colorado, so easing the crop and consequent financial and market losses must include research into resilient crops and crop management. Further, while not discussed at length here, interviewees were also asked to give their perceptions of crop insurance, which is utilized frequently after hail damage. In short, almost all interviewees were quick to deem crop insurance a necessity that lessens the economic impact of hailstorms at least in part. However, rising premiums and lack of coverage on certain crops are common frustrations, and as Interviewee #4 stated, "you hope you never have to use it." Future work aims to bring the insurance sector into this conversation to see how projections of future exposure to hailstorms and sentiments of current farmers can help advise policy creation.

G. Summary and Conclusions

Interviews with fifteen eastern Colorado farmers and ranchers has shed light on the various risk factors and perceptions related to severe hail vulnerability, as well as farmers' reception of and responses to severe hail forecast and warning messages. Interviews drew on the mental models approach, PADM, and vulnerability literature in order to reveal unprimed beliefs about hail, including perceptions of risk and vulnerability from

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hailstorms. Despite the geographically and demographically diverse population, several key themes emerged that are worth exploring further with stakeholders and the weather forecasting communities.

When asked to identify the first things that come to mind in relation to hailstorms across eastern Colorado, most interviewees were quick to express negative affect and emotions as well as frustration associated with crop losses from hailstorms, yet many also conceded that hailstorms are a part of the eastern Colorado culture and thus are expected to be put up with. Many interviewees have observed a recent uptick in hailstorm frequency and severity in the last few years, in contrast to their perceptions that the long-term averages of frequency, size, and season length of hail is not changing. This is consistent with the climatological upward trend of severe hail days across eastern Colorado since 1997 as well as recent years that have broken state records for hailstone size and the percent contribution of significant (50.8-mm+) hail reports to all severe hail reports (Childs and Schumacher 2019). The fact that the rural agricultural community is observing this recent spike in hail activity signals that something meteorological may be happening as opposed to an increasing trend simply due to population bias. In addition to amplifying exposure, interviewees also emphasized a growing sensitivity to hailstorms in recent years due to market fluctuations and crop selection. That hail impacts crop types differently is important and is motivating some farmers to plant alternative crops that better withstand the immediate beating from hail as well as erosion and residue runoff, thus preserving the field's soil for the following growing season. Crop losses are felt heavily by farmers and ranchers, as their livelihoods depend on the profit they earn from crop yields. When hail cuts off an income source, less money is available to upgrade equipment for effective

operations, and a trickle-down effect ensues in the local economy that can be detrimental for employees and felt in the public marketplace.

For the agricultural community, hail severity is measured more by its impacts and less by actual hailstone size. The most worrisome scenario for farmers is small hail either in high volume or wind-driven. This combination of factors can strip heads off wheat plants, flatten fields of corn, and even lead to crops freezing if hail accumulates in the field early in the growing season. Larger hailstones are perceived by farmers and ranchers as primarily causing damage to physical equipment and buildings as opposed to crops.

The interview sample is perceptive of changing weather conditions and tend to pay attention to the weather for its impact on their operations. They associate certain environmental and sky features with increased likelihood of hailstorms, such as high moisture content and green-tinted clouds. When a severe hailstorm is imminent, the majority of interviewees cited cell phone notifications as their primary source of warning messages since their phones are almost always on their person. Most interviewees spoke to the difficulty in predicting the track and intensity of hailstorms, although a common desire to is to know the exact path of a storm. Almost all interviewees admitted that there is nothing to be done to protect crops or livestock, so their focus is on getting humans and physical property indoors. The prospect of severe hail elicits mixed emotions, with some interviewees having learned to accept hailstorms due to their high regional frequency, others feeling anxious or worried about damage and losses, and others feeling dejected and defeated as their agricultural pride takes a hit.

As hailstorms will inevitably continue to affect the communities of eastern Colorado and beyond, it is important to understand the human elements of dealing with them. The

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agricultural community is arguably the sector most directly impacted from hailstorms, not only physically with destruction of crops and equipment but also emotionally as hail penetrates into the livelihoods of farmers and ranchers. This study offers a first look at some of the beliefs and emotions associated with hailstorms and reveals the challenges in both predictability and risk communication of severe hail, as perceived by the agricultural sector. While interview responses may have been influenced by local effects, similar interviews could be conducted in other regions such as the Midwest and Southeast where hailstorms are also common yet driven by different meteorological regimes. Even if options to protect crops during a hailstorm are limited, promoting a greater awareness of the needs and sensitivities of farmers and ranchers in addition to making strides in short-term hail prediction will go a long way toward the overarching goal of protecting life and property from future hail events.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

As the 21st century enters its third decade, calls for climate change regulations and adaptation strategies ring louder than ever. From long-term droughts, raging forest fires, Arctic sea ice loss, bouts of extreme heat, and powerful tornadoes and hurricanes, extreme weather and climate events are gripping attention on the global scale. The all-too-common occurrence of such events has people asking rational questions such as "What's next?" or "How much worse is it going to get?" Yet answering these questions is not as simple as projecting how the climate is evolving and will continue to change the frequency and severity of extreme weather and climate events. The rising impact of weather disasters has just as much, or arguably more, to do with the growing human footprint in society. Put simply, where more people live and play, there is not only more observation of events, but also enhanced exposure to these events. It is therefore imperative that the meteorological community lead the way in collaborating with experts from the humanities to provide a more complete picture of the impending risk.

Tornadoes and hailstorms are two severe weather hazards that routinely occur in the mid-section of the United States and are worthy of consideration of future changes in frequency, spatial distribution, and human exposure. The domain space of eastern Colorado (37-41°N, 102-105.3°W) is selected for its unique topographical influence on the severe weather landscape as well as the stark population divide between the rapidly growing Front Range urban corridor and the sparsely populated, agrarian eastern Plains. To provide a proper framework for these hazards across the eastern Colorado domain, Chapter 2 has presented a series of climatological analyses for both tornadoes and severe

hailstorms. The year 2018 warrants special attention for hailstorm statistics that broke

many state records, which is recorded in Chapter 3. The main science question of changes

in human exposure to tornadoes and severe hail is fleshed out in Chapter 4, considering

projections of hazard frequency, hazard spatial distribution, and population growth. A

Monte Carlo statistical analysis is performed to quantify a range of potential changes in

human exposure, which is sensitive to the overlap between population projection scenarios

and hazard spatial distribution. Chapter 5 investigates the specific impact of hailstorms on

the vast agricultural production of the eastern Plains of Colorado through interviews with

farmers and ranchers that seeks to identify perceptions of hailstorm vulnerability, severity,

and warning message communication. This concluding chapter will provide a brief

synthesis of key results, highlight the limitations and significance of the findings, and

recommend avenues for future work.

A. Key Results

1. Tornado and severe hail climatology

When the full severe weather data record is considered (i.e., since the 1950s), the

eastern Colorado domain shows a statistically significant upward trend in both tornado

and severe hail reports at all intensity and size thresholds. These trends can be explained

in large part by non-meteorological artifacts in the data record rather than a consistent

increase in hazard frequency. For example, the advent of Doppler radar in the mid-1990s

led to a sharp uptick in (E)F0 tornado reports, and the efforts by CoCoRaHS and the NWS to

both encourage and standardize hail reporting practices has propelled the number of

people reporting hailstones, thus inflating the data record. Specific to eastern Colorado is

the dearth of (E)F0 tornadoes in the 1980s decade, when multiple field campaigns

specifically aiming to capture tornadoes and investigate the Denver Cyclone led to an inflation of (E)F1 tornadoes. When the time series is limited to 1997–2017, opposing patterns emerge for the two hazards of interest. Tornado reports and tornado days show decreasing trends over this time period at all intensity ratings, whereas severe hail reports and days continue their upward trend. The fact that the number of severe hail days is increasing over time, and that the national trend in severe hail days is relatively flat since 1997 (Allen and Tippett 2015), suggests a meteorological influence on hailstorm frequency across the eastern Colorado domain. Moreover, recent years have seen record high percentages of hail reports over 50.8 mm relative to all severe hail reports.

Tornado reports show local maxima both near the Front Range urban corridor and in select rural areas further east. These maxima may be due in part to storm chaser bias, as the relatively few paved roads and towns across eastern Colorado lead chasers to frequent particular areas. However, the maximum near the Palmer Divide is likely due to the propensity for non-mesocylonic tornadoes to form in the Denver Convergence Vorticity Zone that sets up in this area on many spring and summer days. Severe hail reports show a more substantial population bias, with the major Front Range cities of Denver, Fort Collins, and Colorado Springs showing bull's-eyes in hail reports. On the other hand, relatively few hailstones are reported on the eastern Plains where population is significantly less. In general, counties with increasing (decreasing) population over time show concurrent increases (decreases) in severe hail reports, whereas county-scale tornado reports and tornado days show more irregular patterns. The seasonal cycle of both tornadoes and hailstorms has become shorter since 1997, which is mostly due to an earlier end to the season. For instance, the period 2008–2018 had an average last day of severe hail of 26

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September, whereas the previous 11 years had an average last day of severe hail of 4 October. The influence of the Southwest Monsoon during late summer is hypothesized as a leading factor in this shortening seasonal cycle, although more work is needed to affirm the relationship.

The environments existing at the time of severe hail and tornado reports are assessed using the SPC Storm Mode database. Relative to severe environments further east, there is generally less CAPE and vertical wind shear (in the median) at the time of severe weather. In this moisture-limited region, dewpoints in excess of 11°C (52°F) appear to be a good indicator for severe weather occurrence. The environments present at the time of severe hail reports are in general more typical of what is expected for strong convection compared to those at the time of tornado reports. Hail environments have higher overall medians in CAPE, shear, helicity, and moisture variables. Given this limited yet intuitive sample, it is not surprising that 96% of all tornadoes occurring in the eastern Colorado domain achieve the weakest (E)F0 rating, and in fact many non-mesocyclonic tornadoes and landspouts also occur here.

The year 2018 was particularly devastating for severe hail across eastern Colorado. Seven days during this year tallied at least one 76.2-mm hail report, which became a new state record. In addition, a record 20% of all severe hail reports were at least 50.8 mm during 2018, shattering the old record of 16% set in 2010. Of note in this hail season was an overnight splitting supercell over Colorado Springs on 13 June that dropped baseball-size hail, a series of supercells that travelled southeastward across the eastern Plains on 29 July, resulting in seventeen 50.8-mm hail reports on just one day, and a 6 August event that

destroyed hundreds of vehicles, injured at least a dozen humans, and killed five animals at the Cheyenne Mountain Zoo near Colorado Springs. Attempts to provide attributions to this rash of damaging events with particularly large hail during 2018 were made using NARR model output. A large ridge was located over the western U.S. during much of the months of July and August, promoting northwesterly flow at mid-levels over eastern Colorado. Combined with frequent episodes of southeasterly low-level flow, anomalously strong vertical wind shear ensued in these two months. The Supercell Composite Parameter, which incorporates MUCAPE, 0-6-km bulk wind shear, and storm-relative helicity in the inflow region, was also anomalously high during these months, indicating increased potential for hail-producing thunderstorms.

2. Projecting future human exposure

High-resolution dynamically-downscaled simulations of control and future climate scenarios (based on the CMIP5 RCP8.5 climate perturbation; Hoogewind et al. 2017) are used to estimate future changes in the tornado and severe hail landscape of eastern Colorado. Thresholds of convective parameters that can serve as proxies for tornado and severe hail reports are computed for a 1971–2000 control period, and the number of days of threshold exceedance are compared between the future and control simulations. Updraft helicity (UH), upward vertical velocity (UVV), and the Air Force Weather Agency (AFWA) Tornado parameter are used for synthetic tornado reports, and UH, UVV, AFWA Hail, and column-integrated graupel are used for synthetic hail reports. The changes in the threshold exceedances for each suite of parameters are averaged to arrive at a spatial change in tornado and severe hail reports in the 2071–2100 period. This method is useful for overcoming the population bias inherent in the SPC data records, wherein severe

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reports are highly correlated to urban areas and are frequently missed across the eastern

Plains despite their regular occurrence. The synthetic report method yields an increase of

one additional day per year of tornadoes and three additional days per year of severe hail

by the future period across much of the northern part of the domain. This corresponds to

approximately 3 more tornado reports and 18 more severe hail reports per year.

Pseudo-global warming (PGW) methods are used to validate the domain-wide

increase in annual tornado and hailstorms predicted by the synthetic reports analysis.

Continuous 13-year simulations have been run over the CONUS to represent current and

PGW environments, using WRF and forced by ERA-Interim every 6 hours (Rasmussen et al.

2017). The PGW simulation once again incorporates the CMIP5 ensemble mean climate

perturbation from the RCP8.5 scenario. A variety of convective parameters are output,

enabling a comparison of the convective populations between control and PGW scenarios.

Across the eastern Colorado domain, an increase in the highest reflectivity bins (e.g. > 50

dBZ) for one select year is seen in the PGW scenario, whereas smaller reflectivities occur at

around the same frequency or even decrease in the PGW scenario. As higher composite

reflectivity generally indicates more intense rain rates and convection, including but not

limited to supercell thunderstorms capable of producing severe hail and tornadoes, an

increase in this convective population is predicted in the future climate. In addition,

domain-averaged MLCAPE and MLCIN is captured at 3-hourly intervals for model times in

which MLCAPE > 500 J kg^{-1} in both the control and PGW output. Compared to the control

run, the PGW environment contains more simultaneous occurrences of high CAPE and high

CIN, and less simultaneous occurrences of low CAPE and low CIN. In other words, the

atmospheric cap is stronger, and yet the positive buoyancy is also stronger, enabling the

cap to break more often in the PGW scenario, implying an increase in vigorous convection

and in turn a potential greater frequency in tornadoes and hailstorms across eastern

Colorado in the future and affirming the synthetic reports analysis.

Because changes in meteorology are only one piece of the human exposure puzzle,

population projections from the Shared Socioeconomic Pathways (SSPs; Jones and O'Neill

2016) are downscaled and clipped to the eastern Colorado domain. The five SSPs each

produce a different population arrangement by the year 2100 due to their dependency on

factors such as education level, wealth, immigration, and industry. Most SSPs predict

growth across much of the urban corridor and stagnant or slightly decreasing population

across the eastern Plains (with subtle differences in and around small towns). At the

extremes are SSP5, which produces massive population growth area-wide, and SSP3, which

projects a loss of population across all areas except city centers.

Combinations of the aforementioned changes in hazard frequency, hazard spatial

distribution, and population, are input into a Tornado Monte Carlo model (TorMC; Strader

et al. 2016) and a similar Hail Monte Carlo model (HailMC). These models are run for 1000

years and ingest a rasterized cost surface of population change as well as a rasterized

hazard weighting surface based on the respective change in hazard frequency across the

domain projected by the high-resolution dynamically-downscaled WRF output. Essentially,

the model counts how many people live underneath tornado tracks and hail swaths in a

base case simulation and a suite of other scenarios. When hazard frequency and spatial

distribution is held constant to their control distributions, an increasing human exposure

to severe hail is seen for all SSPs (up to 161%), and an increasing human exposure to

tornadoes is seen for all SSPs except SSP3 (up to 155%). When population is held constant

at its base case level and hazard frequency is increased, comparatively smaller increases in

human exposure are seen, indicating that the population effect is greater than the

meteorological effect when considered independently. The greatest percent change in

human exposure is seen when hazard frequency *and* population are changed, but the

spatial distribution of the hazards are held constant to their control distributions. In this

case, SSP5 yields a 178% increase in human exposure to severe hail and a 173% increase in

human exposure to tornadoes. In the final set of simulations, in which every factor is

allowed to change to its future projection, the maximum increase in human exposure for

tornadoes falls to 117% for SSP5, and every simulation for severe hail results in decreasing

human exposure. This implies that severe hailstorms are projected to increase most across

northeastern Colorado, where population is not anticipated to increase enough to offset the

losses in human exposure. However, the vast amount of agricultural land in this area

would imply an increasing exposure for crops. by the end of this century.

3. Agricultural perceptions of hailstorms

To measure how farmers and ranchers across the domain space perceive their

exposure to, the severity of, and the warning messages for hailstorms, fifteen structured

interviews were conducted in Summer 2019. The interview protocol drew upon several

social science methods, including mental models, Protective Action Decision Model, and

vulnerability constructs. Respondents were recruited primarily via county extension

agents and CoCoRaHS, and interviews lasted an average of 28 minutes. The interview

sample proved fairly representative to the agricultural landscape of eastern Colorado, with

their most frequently raised crops being wheat and corn. Interviewees ranged from a 3-acre vegetable farmer, to large ranchers farming in excess of 50,000 acres.

Perceived vulnerability to hailstorms was assessed according to the definition put forward in Cutter et al. (2000) that incorporates both exposure and sensitivity. The majority of interviewees perceive eastern Colorado as a hotspot for hail activity and hailstorms as a hazard that must be put up with each year. In general, interviewees did not note any long-term changes in their exposure, as measured by hailstorm frequency, but did cite a recent uptick in particularly damaging events. This affirms the observational upward trend in hail reports and hail days in recent decades. Perceived sensitivity, defined as the ability to cope with the effects of hailstorms, were varied among the respondents and depended upon factors such as crop selection, time of year, and market trends. Most interviewees did note an amplification of their sensitivity to hailstorms over time due to market trends and financial strains. Relatedly, the most commonly mentioned negative impact of hailstorms was crop loss and its attendant financial losses. Interestingly, of most concern to farmers are small hailstones, either in large volumes or driven by strong winds, because these are the ones that most readily strip crops and lead to steep financial losses. While large hailstones are also damaging, particularly to physical structures and equipment, they are not perceived to be as worrisome to farmers and ranchers.

Unsurprisingly, farmers keep a close eye on the weather, as their livelihoods often depend on it. Environmental cues such as high humidity and green clouds are used frequently as omens for impending hailstorms. The most popular channel for receiving hail warming messages is through cell phone notifications. Nine and six interviewees

respectively said they never use the NOAA Weather Radio or television to receive warnings. Upon receipt of a warning for severe hail, there is very little farmers and ranchers can do to protect crops and livestock. Most interviewees expressed deep emotions regarding an impending hailstorm. Some have learned to accept hailstorms as commonplace and leave their impacts up to a supernatural power, while others respond with anxiety at the prospect of losing a valuable harvest. Still others expressed feelings of dejection and defeat as the pride they have in growing crops and livestock for the good of the general public is deflated, and they are left to pick up the pieces and deal with the repercussions of crop loss and insurance claims. While forecasting hail is admittedly challenging to farmers and ranchers, there is a desire for improved predictability of hail surface characteristics and hailstorm track, emphases that provide avenues for future research.

B. Challenges and Limitations

As with any study of this depth and that utilizes methods across multiple disciplines, limitations exist that warrant mention. One of the unique advantages of this work is its focus on the relatively localized domain of eastern Colorado. This allows for climate change impacts to be more easily interpreted by individuals living within the domain space, as opposed to the public having to translate regional or national findings to their local place of residence. That said, focusing on eastern Colorado dictates that, compared to a larger domain, the number of tornado and severe hail events in the data record are considerably fewer, which has implications for statistical significance of climatological trends and promotes a larger influence from the biases within the SPC database. Some of the intricacies of the tornado and hail data records for eastern Colorado, such as the non-

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meteorological dearth of (E)F0 tornadoes in the 1980s, prohibit any robust analysis of trends prior to 1997. A larger domain would have allowed the interview sample discussed in Chapter 5 to be larger and have a more diverse array of crops and livestock; nevertheless, the sample size obtained has been shown to be quite representative of eastern Colorado.

The Shared Socioeconomic Pathways represents only one of several recently released population or housing unit projection data sets (e.g., SRES, U.S. EPA; Jones and O'Neill 2013). Each have their own methods of calculating how population may change in the future. While the SSPs have been selected for their proven utility in natural hazards research, the sensitivity of human exposure to the overlap between population projections and meteorological changes found in Chapter 4 means that choosing another population data set may result in a slightly different range of potential exposure. Further, the SSPs rely on national-level demographic assumptions, and thus the population projections are downscaled using a gravity-model approach developed at NCAR, which can introduce subtle artifacts when analyzing across small domains (Jones and O'Neill 2013, 2016). In all likelihood, the actual population landscape of eastern Colorado by the year 2100 will not match any one SSP, so thus the changes in human exposure generated by TorMC and HailMC represent a range of uncertainty rather than the exact number of people who may be exposed to the hazards.

The dynamical downscaling approach used to generate synthetic reports in Chapter 4, which uses a mesoscale model in which convection can initiate within large-scale environments, is preferred to using output from global climate models (GCMs) since a

conclusion of more favorable environments for severe weather in the future climate says nothing about whether those favorable conditions can actually be realized and initiate convection. That said, the particular simulations by Hoogewind et al. (2017) in which the convective proxy output is taken, use the CMIP5 experiment and the most aggressive scenario for radiative forcing (RCP8.5). Using less aggressive RCPs could alter results and provide an alternative change in frequency of eastern Colorado severe weather. Further, using an ensemble rather than a single GCM would provide more realistic representation of changes in convection, but the computationally expensive nature of these downscaled simulations presents challenges to offering additional scenarios or ensembles.

Some important atmospheric processes and variables related to severe convection are not explicitly accounted for in the climate change simulations considered here. For example, the regional climate model (RCM) setups do not consider aerosol affects, but any changes in aerosols in a future climate could alter concentrations of cloud condensation nuclei and affect hailstone growth. Local moisture budgets, which are absent from the dynamical-downscaled climate simulations considered here, could be very important particularly in eastern Colorado where any land use changes could have a direct effect on groundwater from crop irrigation. In fact, improved PGW simulations that do account for groundwater help offset the Great Plains dry bias inherent in previous iterations. Finally, the nature of the PGW methodology that institutes spectral nudging of large-scale variables above the planetary boundary layer entails that vertical wind shear, such as that between 0 and 6 km which is often used to diagnose supercell strength, cannot be calculated.

It should also be said that synthetic reports are, by definition, man-made, and thus relies upon proxies for tornado and severe hail reports rather than the hazard occurrences themselves. However, the fact that the national-level results of hazardous convective weather found by Hoogewind et al. (2017) compare well to large-scale environmental projections and yet provide more robust details of seasonal variations in the realization of these environments give credence to the dynamical downscaling approach and motivate future developments using this method.

The Tornado and Hail Monte Carlo model designs follow Strader et al. (2016), and effort is taken to eliminate sources of bias in the SPC data records such as through selection of reports that are limited to certain intensities and years, and placement of simulated tornadoes and hail events based on historical and future projected weighting surfaces. To count the number of people underneath tornado tracks and hail swaths, the intersection cost-extraction technique is utilized, whereby if a track or swath overlaps at least a part of a grid box, all people living within that grid box are assumed to be exposed. Therefore, changing the grid box size, or employing alternative cost-extraction techniques put forward in Strader et al. (2016), could result in slightly different changes in human exposure. As stated by Strader et al. (2016), as spatial resolution of the raster surface increases, the cost estimates will be more accurate. Hail swaths are defined in this study as 0.5 km X 0.5 km rectangles. Since the concern is with percent changes in human exposure, the size of the hail swath is not critical as long as hail swaths are unchanged in all MC simulations. It should be stated, however, that hail swaths are rarely uniform rectangles, and can extend for several kilometers. In addition, a variety of hailstone sizes can fall within a hail swath, which is not represented in the model. As mentioned by Strader et al. (2016), TorMC and

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HailMC could also be improved by ingesting vector-based cost surfaces and running the models at higher resolutions to produce seasonal exposure statistics. This study has proven the utility of the TorMC framework introduced by Strader et al. (2016), however, and expanded its applications by applying a spatially weighted change in hazard frequency and including analysis of hailstorm exposure over a smaller localized domain.

Additional limitations exist in the interview study detailed in Chapter 5. Effort was taken to make the opportunity for participation available to as wide an audience as possible across eastern Colorado through a consistent initial contact with county extension agents. However, the sample was ultimately limited to those who had contact with this extension agent and could respond to the call for interviews. Participants were also recruited at a wheat field day and through a list of CoCoRaHS hail observers, but there was no a priori distinguishing of participants based on any demographic or cultural information. Sixteen participants were scheduled for interviews, of which one backed out; otherwise, no participant who expressed interest was turned away. The final interviewee sample was geographically and agriculturally diverse, with twelve counties and sixteen different crops and livestock represented. The number of common themes expressed among the sample was encouraging, but the findings could potentially be strengthened by a larger sample size. This study can also be a jumping off point for similar analysis with farmers in other regions of the U.S. that see hailstorms yet raise a different set of primary crops and livestock. The results presented herein could be an artifact of the local perception of dryland farming in one of the most hail-prone regions of the country, but without a wider sample set this cannot be definitively known. It is also not possible to assess how an interviewee's recent life experiences could have impacted his or her

responses. For example, responses could be biased based on whether a hailstorm had impacted one's property in the weeks before the interview. The reflexive thematic analysis performed on the qualitative data carries the potential bias associated with self-reporting. No a priori assumptions were made about common themes, allowing the data to speak for itself (Braun et al. 2018). However, this required the author to deduce themes within the interview transcripts subjectively. Although cross-checked with an expert for coherency, a third independent researcher could have potentially found other important themes in the data. Finally, the interview protocol and qualitative data analysis draws upon multiple modeling approaches rather than following any one method strictly. For example, the mental models approach (Morgan et al. 2002) and Protective Action Decision Model (Lindell and Perry 2012) motivate sections of the interview protocol, but their systematic structures are not replicated entirely. While the approach taken here allows for a more integrative interview, the benefits from a proven, structured protocol with a representative sample size are not absorbed. Despite the mentioned limitations, this work bears great significance on many facets of society and inspires continued research ventures.

C. Significance and Future Work

1. Significance

In the warming world in which we live, there is a growing emphasis on research within the weather enterprise that investigates the impacts of climate change on natural hazards, extreme weather and climate events, natural resources, and demographic footprints. This study not only adds to this body of work but makes significant contributions to it in its unique approach in utilizing multiple data sets and methods to

model the intersection of meteorological and human factors contributing to changes in the severe weather landscape across a localized domain.

Eastern Colorado is perhaps underappreciated in the severe weather discussion, but in fact is a local maximum in both tornado and hail activity, having a large influence on its convective weather from the Rocky Mountains and other smaller topographic features such as the Palmer Divide. Furthermore, the socioeconomic variability in this region is such that impacts from these events may be experienced and broadcast very differently. It is the hope that this doctoral study showcases the utility in small-scale analysis and provide a framework for similar analyses in other localized regions of the U.S. In fact, all of the methods presented herein could easily be replicated in other spatial domains and even for other convective weather hazards.

The updated climatology of eastern Colorado tornadoes and hailstorms creates a trellis to serve as a reference for the local community. Having modern statistics for tornado and severe hail reports and days, and their spatial representation, are critical for understanding local trends and projecting future changes. The results presented here also address key considerations in how to properly treat biases and limitations in severe weather data sets, which can be used when the next climatological updates are needed. In fact, the NWS office in Boulder has already placed the published climatological results (Childs and Schumacher 2019) on the list of required reading for new employees in order to help understand the severe weather landscape and biases across eastern Colorado and facilitate new avenues for learning.

This work is also novel in its sequence of methods to incorporate both hazard and population projections in a Monte Carlo framework to assess changes in human exposure.

Never before have SSPs been used in conjunction with dynamically-downscaled synthetic tornado and severe hail reports to reveal the overlapping effects of population growth and shifts in severe weather occurrence. This work has also presented a method to overcome population bias inherent in SPC tornado and hail data when projecting future hazard spatial distribution, namely by adding changes in synthetic reports between a future and historical climate simulation to a population-biased control spatial distribution of hazards, thereby allowing for the fact that more severe weather will continue to be reported where people live but also allowing meteorological effects to manifest independent of where people live. This approach thus can give a more complete picture of the spatial risk and human exposure from tornadoes and hailstorms. The application of high-resolution weather model output and pseudo-global warming simulations on a small domain is also innovative. To-date, much of the literature on climate change impacts on convection and severe weather hazards, including motivating papers for this work, has been limited to regional findings (e.g., Gensini and Mote 2015, Hoogewind et al. 2017, Rasmussen et al. 2017, Trapp et al. 2019), but here existing methods are applied more locally on a 1-km grid to help extract small-scale climate change effects, as well as reveal model limitations within and near mountainous terrain.

Another major significance of this work is its application to decision-makers from a variety of sectors. At its core, revealing how the human exposure to the two primary severe weather hazards of eastern Colorado may change by the end of the 21st century highlights the importance of the weather-societal interface in risk analysis. It is tempting for the meteorological community to rely solely upon weather model output and new machine learning techniques in advancing understanding and prediction of convective

hazards, and likewise more societally-bent scientists desire increased public engagement and interviews to understand the socioeconomic factors governing one's vulnerability. However, it is the intersection of these two pathways where the most progress toward protecting life and property can be made, and this doctoral study helps to affirm that both meteorological and human factors determine one's true risk and exposure. This realization can then directly impact how decision-makers plan and enact future policies for the state of Colorado. For example, urban and city planners can use these findings to help formulate growth strategies for the Front Range urban corridor as well as smaller towns in the eastern Plains based on the future projections of tornado and hailstorm frequency and spatial distribution. When developing land for a new neighborhood, thought can be given to hailstorm mitigation strategies, such as offering garages for vehicles and placing sensitive utilities under protective coverings. Businesses and recreational attractions are also encouraged to take steps toward protecting their employees and visitors, such as offering covered parking or having clear and practiced severe weather plans. As an example, in the wake of the Cheyenne Mountain Zoo hailstorm of 2018, zoo leadership helped implement better protective shelters for people and animals during the recovery phase (CBS4 Denver 2019). It goes without saying that meteorologists can also benefit greatly from these findings, as they not only affirm the respective roles played by environmental variables in promoting severe weather across eastern Colorado, but also provide a look at future projections of these hazards which can help answer questions from and teach their viewers and readers about tornadoes and hailstorms in their own backyards. Emergency managers can also be better equipped in resource allocation and understanding the needs of the agricultural sector when there is a risk from hailstorms.

While population growth in tornado- and hail-prone areas of Colorado is unlikely to be halted, persons moving here can also take precautionary steps, such as considering basements and hail-resistant roofing, or simply developing a family safety plan. It is likely that many people moving into eastern Colorado are not aware of the risk tornadoes and hailstorms pose in this region outside of the traditional "Tornado Alley," so simply educating the public about both the climatologies of these hazards and the potential future projections presented here can go a long way toward a weather-ready community.

It should be stated that, in a sense, the aforementioned benefits of the findings in this study for decision-makers are theoretical, as we do not know the extent of their utility. For example, Dilling et al. (2017) performed a case study analysis of local governments within intermountain west states, including Colorado, and found that external pressures and funding are more likely than perceived hazard risk to compel creation of local all-hazards risk plans. Nevertheless, having an idea of where to expect the greatest increases in future tornado and severe hail activity over eastern Colorado in the future, and having a better understanding of the needs and desires of the agricultural community related to hailstorms, is certainly advantageous and can be of great worth to the local community. In fact, the agricultural sector is not usually included in focus groups or discussion regarding improving severe weather prediction and warning communication, as they are not a core partner of the NWS. However, as the results in Chapter 5 reveal, farmers share some important concerns regarding hailstorms that impact their land in eastern Colorado. These concerns are traditionally not heard by meteorologists, so this study is significant in its aim to give the agricultural sector a voice within the weather community. It should be noted that efforts to incorporate agricultural needs within the NWS framework do exist, even in

Colorado, but this study recommends paths forward to stronger partnerships between these two sectors, especially given the importance of agriculture on local and state economies and the prevalence of convective hazard impacts on agricultural lands.

2. Future work

The results of this multi-faceted study lend themselves well to follow-up investigations and motivate ongoing and upcoming research endeavors. Given the very localized nature of both climate change impacts on convective hazards and the influence of human factors in altering exposure revealed in this study, a worthy endeavor will be to apply the methods utilized here to other locations. Of particular interest for comparison with the eastern Colorado results are regions that experience tornadoes and/or hailstorms and are also meteorologically influenced by terrain features. Some areas within the Southeast U.S. fit this description, as well as international locations such as Argentina, in the lee of the Andes Mountains, and Switzerland, near the Alps. In fact, the recent RELAMPAGO field campaign in Argentina has shed light on the frequent hailstorms and other convective hazards in this region (Bruick et al. 2019), and Swiss researchers are currently creating a national hail climatology for their country and have also found increasing hail frequency and sizes in future climate simulations (Martynov et al. 2017). Adding population effects to the findings in a Monte Carlo framework would be intuitive in assessment of human risk in these countries. Moreover, it is important to understand how complex terrain influences both future hazard occurrence, due to spatially and altitudinally varying climate change, as well as model performance of future and current climate simulations.

Both high-resolution dynamical-downscaling techniques and pseudo-global warming approaches continue to be improved upon by using higher spatial resolution, incorporating improved radar data or reanalysis (e.g., ERA5), and removing biases present in previous iterations by including groundwater effects. In addition, it is becoming more apparent that simulating a range of Representative Concentration Pathways (RCPs) rather than solely the so-called 'business as usual' or 'high-end' RCP8.5 scenario can give a more realistic suite of projections (Hausfather and Peters 2020). Such advancements take time and ample computing power, but progress is ongoing for new PGW CONUS runs and dynamical downscaled output of a variety of convective parameters over the U.S., which can then be utilized over smaller domains to gain an updated picture of how convective hazards may change in the future climate. Still, important variables for severe weather such as vertical wind shear are not well represented by the PGW method since quantities above the planetary boundary layer are nudged to the ERA-Interim reanalysis (Liu et al. 2017).

Another major realm of future work focuses on risk communication for hailstorms and improvements in hail surface characteristics predictability. Figure 6.1 presents one potential pathway for extending facets of hailstorm findings through three research objectives (ROs). To better understand the current challenges and best practices of communicating hailstorm risks to the eastern Colorado domain, a survey of NWS meteorologists at forecast offices responsible for the eastern Colorado can be conducted (RO1). These surveys will incorporate some of the prevailing themes from the interviews of farmers and ranchers. One area of particular interest is the emphasis on small hail, either wind-driven or in large quantity, conveyed by the sample. Currently, a severe

thunderstorm warning for hail is only issued when hailstone size is expected to exceed 25.4

mm. Thus, adding new warning language that accounts for wind-driven hail and large

volume of hail below current severe limits, will be proposed in the survey for forecaster

feedback. This would be an example of probabilistic hazard information (PHI) that is now

also included in tornado warnings. Updating severe thunderstorm warning language as
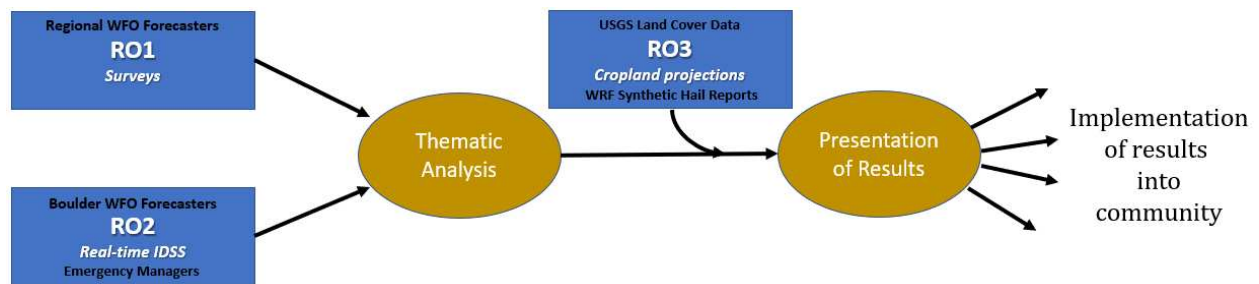
Fig. 6.1: Conceptual flowchart of three ROs and related analysis pathway proposed as an extension of the interview study with eastern Colorado farmers and ranchers.

such implies that meteorologists can give a reasonably accurate prediction of hail size,

volume, and wind speeds. While strides are being made, this study motivates continued

efforts to improve understanding of, for example, what makes one storm produce giant hail

and another storm produce a large volume of small hail, or what dictates the duration of

hailfall within a storm. Future field campaigns and model improvements to better

represent hail microphysical processes are recommended. It is also of worth to observe

nowcasting of severe hail events at local NWS offices to glean how decisions are made and

warnings are issued in urban versus rural areas (RO2). This speaks to the perception of a

disconnect in attention given by meteorologists to those living along the Front Range and

those across the eastern Plains, and the goal would be to see how a high-risk *rural* hail

scenario is forecasted and communicated by forecasters relative to one set to impact more populated areas.

A final piece of the proposed extension pathway (RO3) is to incorporate high-resolution land use projections for the Great Plains region from the USGS FORE-SCE model under different climate scenarios (Sohl et al. 2018) into HailMC, thus yielding a range of changes in end-of-century agricultural exposure. Chase et al. (1999) showed a connection between land use changes and the mountain-plains circulation that helps drive sensible weather in the region, so one can imagine that hailstorm exposure may also be influenced by ongoing conversions in land cover. This information can be of benefit to crop insurance agencies in their development of future policies, as well as the agricultural community itself. Even in the immediate future, farmers can seek alternative solutions to hail-induced losses, such as growing crops with greater resiliency and promoting nutrient-rich organic matter within soils. Over time, regional perceptions of hailstorm vulnerability and warning message efficacy can be charted and taken to the meteorological community to promote stronger relationships and renewed efforts to communicate effectively to the agricultural sector.

Finally, while this study has analyzed annual tornado and severe hail events, in part due to the sample size, projecting monthly distributions of these hazards could help pinpoint times of year expected to become more or less conducive to tornadoes or hailstorms over time, as well as help shed light on the shortening season lengths. Relatedly, given the importance of moisture in promoting strong convection in the dry Colorado climate, as well as its contribution to hail growth and melting, it is of worth to analyze trends in moisture variables over time across the domain using the newly released

ERA5 reanalysis, as well as to assess how moisture is projected to change under future climate or pseudo-global warming simulations. Moisture trends in the region, particularly during the Southwest Monsoon season in the second half of the summer could help verify the earlier end to the eastern Colorado severe weather season. Radar applications, including polarimetric variables and hydrometeor identification algorithms have been used to identify the presence of hail of different sizes (Witt et al. 1998, Kumjian et al. 2014, Allen et al. 2020b), and assimilation of radar data into numerical weather prediction models have shown promise in nowcasting (Martius et al. 2018). Future advancements in PGW techniques that can incorporate projections of polarimetric variables within individual storms would go a long way toward assessing changes in hail growth and intensity, particularly in hail-prone regions such as eastern Colorado.

The overarching goal of this doctoral study has been to bring to light the complex yet critical interplay between meteorology and social factors when considering future changes in the human risk from and exposure to convective weather hazards. In the eastern Colorado domain considered, not only is the potential for severe thunderstorms capable of producing large damaging hail and tornadoes amplifying due to environmental changes, but the explosive population growth along the Front Range and spilling out onto the eastern Plains presents a potential recipe for disaster if risks are not properly communicated and caution is not heeded. While there is uncertainty in exactly how the meteorological and societal factors will shift over time – as has been emphasized here – the time to think critically about how to mitigate negative impacts from climate- and human-induced changes in the Colorado severe weather footprint is now. For at its core, the climate change question, particularly related to severe convective hazards, is not

manifested at the regional or national level, nor is it concerned with governmental interests. Rather, it is about individual persons at local scales with real-world issues, facing the effects of hazards such as tornadoes and hailstorms on his or her livelihoods. It is about the wheat farmer in rural eastern Colorado who just lost an entire crop from a hailstorm having to tap into crop insurance yet again and feeling crushed in spirit from the inability to produce what he or she has promised. It is about the vacationer at the Cheyenne Mountain Zoo running for cover and then watching as baseball-size hailstones shatter glass, destroy vehicles, and pelt animals. It is about the family who just moved to the easternmost plot in a new development in the expanding suburbs witnessing without obstruction a tornado innocently meandering the barren land to their east and then wondering how long before that same tornado is instead tracking over homes in their growing neighborhood. Understanding the importance of the local perspective on the broader communal landscape and the desire for weather information to be valid where a person lives motivates the ongoing research foci on short-term and seasonal predictions of severe weather in a changing climate, new insights that can help drive land use and urban planning, and improved education and outreach in both urban and rural spheres. Such initiatives can help ease the anxiety, increase awareness, and ultimately protect the lives and property of the hard-working people of eastern Colorado.

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Interview Number _____ Date _____ Time _____

Thank you again for agreeing to let me interview you today. Please say what you think or believe about the following questions. Remember that your name will not be associated with your response in our analyses or reports. There are no right or wrong answers, and your answers will be most helpful to us if they are what you really think. <u>If I ask a question that you've already answered, please feel free to say so and refer to your previous answer.</u> I'll be taking notes while you're talking, and these are to help me follow along with what you're saying.

<u>General prompts</u>:

> *You mentioned ___, can you tell me more about that?*
> *Does anything else come to mind?*
> *You've mentioned ___, ___…. , does anything else come to mind?*
> *Please say whatever comes to mind.*
> *Can you elaborate on ___?*

QUESTIONNAIRE

Before I begin recording, there are a few quick demographic questions I'd like to ask to help us better understand the agricultural history and

experiences with hail that our complete sample has had. [Ask questions on questionnaire]

HAIL

1. ○ Tell me about hail storms …
   [**Prompt based on concepts mentioned**]

2. ○ **[Prompt if Colorado was not specifically mentioned]**
   Tell me about hail storms in eastern Colorado…

EFFECTS

I'm now going to ask you about some of the effects and risks associated with hail.

3. ○ [If have mentioned: As you mentioned] How does hail affect your daily life?

4. ○ How do the effects of hail specifically impact your work/career in agriculture?

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5. ○ According to you, what are some of the risks associated with hail storms *in eastern Colorado*?

6. ○ Which of those risks you just mentioned do you think is the most serious?

7. ○ "Severe hail" is defined by the National Weather Service as hail that is 1" or larger. When would you consider a hail event to be "severe?"

8. ○ Which of the following is more worrisome to you as a farmer: (a) A hail storm that produces a lot of small hail that accumulates like snow or (b) A hail storm that produces a few very large stones in excess of 3" (or "baseball-size")? **Why?**

PERCEPTION OF RISK AND VULNERABILITY

I'm now going to ask you about your perceptions of risk and vulnerability associated with hail storms. There are many different ways to measure how vulnerable someone is to a hail storm. Here, I'm going to focus on a classic definition that takes into account one's exposure and sensitivity.

9. ○ First, thinking about exposure to hail storms, on a scale from 1 to 10, what do you think is the chance of severe hail occurring on your property over a given year? [**Prompt: (If no explanation) You gave a rating of ___. Why?**]

10. ○ Do you think that number has changed over time? In other words, do you think the occurrence of hail storms is changing over time? If so, how?

11. ○ Sensitivity can be defined as the social, economic, or demographic characteristics that affect someone's ability to deal with the impacts of a hazard, in this case hail. With that in mind, on a scale from 1 to 10, how sensitive do you think you are to the impacts of a hail storm, with 1 being the least sensitive and 10 being the most sensitive?
[**Prompt: (If struggling) Another way to look at it would be to ask how affected you would be if a hail storm occurs on your property.**]

12. ○ [If not already mentioned] In your opinion, do you think you have become more or less sensitive (or no change) to hail storms over time?

13. ○ [If have mentioned: As you mentioned] What factors contribute to your perceived sensitivity from hail storms?
[**Prompt: (If quiet) Think about things like the number or types of crops you farm, your farming practices, the structures and buildings that are on your property, population, insurance, large/small operation, etc.?**]

14. ○ [If not already mentioned] In your opinion, do you think there has been any changes in either the occurrence of or sensitivity to hail storms across eastern Colorado as a whole?

15. ○ [If not already mentioned] In your opinion, has the size of hail stones that you have observed changed over time? If so, how?

16. ○ [If not already mentioned] The length of the severe hail season is defined as the number of days between the first hail report of at least 1" in the year and last hail report of at least 1" in the year. Have you experienced any change in the length of the hail season over time?
[**Prompt: If yes, would you say that shortening/lengthening is happening at either the beginning or the end of the season or both?**]

EVENT-BASED RESPONSE (PADM)

I'm now going to ask a series of questions about how you receive and respond to hail warning information.

17. ○   Do you get weather forecasts and/or warnings when there is a threat of severe hail storms?

18. ○   How regularly do you get warnings from the following sources? *(source/channel)*?
(Show card with 'Always', 'Most of the Time', 'Sometimes', 'Rarely', 'Never' options)

(a) Television
(b) Weather Radio
(c) Phone Alert
(d) Private Sector (app or private company),
(e) Online
(f) Friends and Family

19. ○ [Based on previous answer] What is your *preferred* source of forecast messages for severe hail *(source)*? Why?

20. ○   To what extent do you feel that the hail forecasts and/or warnings that you get include information about the size of hail stones?
[**Prompt] How do you know how large the hail will be *(message)*?**

21. ○   To what extent do you consider warning messages for hail effective and accurate *(effect)*?

22. ○   What is the single most important piece of information you want to know about a coming hail storm?

23. ○   How do you feel when you receive a warning message for severe hail in your area?

24. ⭕ What action steps do you take to respond to a warning message or threat of severe hail?
[**Prompt: Seek more information? Alert family or friends? Protect crops/property?**]

25. ⭕ [If not already mentioned] What are some environmental clues that a hail storm is coming?
MITIGATION

This section can be skipped if pressed for time

Almost done! I want to ask just a few questions about some mitigation practices.

26. ⭕ Are there any things that you do to protect yourself or your property from hail before the season begins or further in advance? What?

27. ⭕ Are there any changes that you are considering to make in your personal and/or agricultural life to help protect against future hail storms?

28. ⭕ How does crop insurance affect your perceptions of hail risk?

CLOSING

In closing . . .

29. ⭕ Was there anything we didn't ask that you think we should have asked?
[**Prompt: If yes, allow them to share that issue**].

Thank you for your time. We appreciate your participation in our study. I will keep you posted on the results of this study once it is published.

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QUESTIONNAIRE

Please answer these short questions to the best of your ability. These answers will help the researchers better understand the agricultural history of the study sample and their experiences with hail.

1. Which Colorado county do you live in?   _____

2. What is the town nearest to your residence?   _____

3. How many years have you lived in eastern Colorado (*show map)*?   _____ years

4. How many years farmed at your current residence?   _____ years

5. How many years have you farmed overall?   _____ years

6. Approximately how many acres do you currently farm?   _____ acres

7. What are the primary crops that you farm / livestock that you raise?   _____

8. Are you a CoCoRAHS observer who measures and reports hail stones that fall on your property (circle one)?   YES   NO

9. Have you ever filed an insurance claim for crop loss due to hail damage (circle one)?   YES   NO

10. If yes, did you file an insurance claim in 2018 or so far in 2019 (circle one)?   YES   NO