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A geographical analysis of warm season lightning/landscape interactions across Colorado, USA

Brandon J. Vogt [a,*], Stephen J. Hodanish [b]

[a] University of Colorado Colorado Springs, Department of Geography and Environmental Studies, 1420 Austin Bluffs Parkway, Colorado Springs, CO 80918, USA

[b] NOAA/National Weather Service, Pueblo Forecast Office, 3 Eaton Way, Pueblo, CO 81001, USA

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A B S T R A C T

This article analyzes lightning/landscape interactions across the State of Colorado. Ten years (2003–2012) of warm season cloud-to-ground (CG) lightning activity are mapped at 500 × 500 m^2 to characterize the distribution of thunderstorm activity. Geospatial analyses quantify lightning activity by elevation, physiographic region, and mountain range, and time-series animations outline the general movement of thunderstorms. From these spatio-temporal perspectives, our objective is to elucidate lightning/landscape interactions as they occur over a topographically and climatologically diverse landscape. The information aids meteorologists by exposing orographic and rainshadow effects, mesoscale meteorological effects, fluxes of moisture sources, thunderstorm initiation zones, and thunderstorm movements. Other benefits extend to wildland fire managers, those who maintain lightning-vulnerable infrastructures, and, from a human risk perspective, an overall awareness to those who work and play outdoors. Major findings include (1) elevation alone does not determine the degree of lightning activity, (2) across the state's mountain ranges, lightning density varies considerably, but the number of lightning days does not, and (3) the time of lightning initiation and maxima varies by elevation, with higher mountain elevations experiencing most activity 1 h before lower mountain elevations, and 3 h before lower Great Plains locations.

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1. Introduction

Lightning maps that display multiple years of strike location data distill spatio-temporal trends in lightning activity and support a number of disciplines and applications (Holt, Hardaker, and McLelland 2001; Bentley & Stallins, 2005; Stallins & Bentley, 2006; Mayet, Knight, & Grab, 2015). In meteorology, the ability to document lightning patterns across the earth's surface contributes to a deeper understanding of atmospheric processes (Schaaf, Banta, and Wurman 1988; Rose, Stallins & Bentley 2008; Cummins, 2012, 2014; Hodanish & Wolyn, 2012; Mäkelä, Shrestha, and Karki 2014; Miller, Ellis, & Keighton, 2015), and enhances the forecasting of thunderstorms (Fuquay1980; Stroupe, 2004) and the estimation of precipitation (Soula, Sauvageot, Molinié, Mesnard, & Chauzy, 1998; Ezcurra, Areitio, and Herrero 2002; Xu, Adler, and Wang 2014). Because cloud-to-ground (CG) lightning strike density is directly related to overall risk to structures and humans, lightning geographies, such as lightning strike density maps, are of interest to those who maintain infrastructures vulnerable to lightning (Hameed, Ahn, and Cho 2010; Rodrigues, Mendes, and Catalão 2011), and to agencies involved with wildland fire management (Meisner et al. 1993; Krawchuk, Cumming, and Flannigan 2009; Narayanaraj & Wimberly, 2012; Guo et al., 2016; Paz et al., 2016). Similarly, lightning geographies are pertinent to those who incorporate wildland fire incidence into studies of climate change (Goldhammer & Price, 1998; Harley, Grissino-Maye, Horn, & Bergh, 2014; Tang et al. 2015). Last, understanding lightning incidence across a region is important from a lightning susceptibility/risk awareness perspective (Stallins & Bentley, 2006; Stallins & Rose, 2008; Lein & Stump, 2009; Cooper & Holle, 2010; Shepherd, Stallins, Jin, & Mote, 2010; Davis et al. 2014; Arpaci, Malowerschnig, and Vacik 2014). For example, this information supports risk assessment in the vicinity of large outdoor spectator events (Livingston, Nielson-Gammon, and Orville 1996; Gratz & Noble, 2006; Woodrum & Franklin, 2012, pp. 1–6) and on popularly

* Corresponding author.
E-mail addresses: bvogt@uccs.edu (B.J. Vogt), steve.hodanish@noaa.gov (S.J. Hodanish).

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visited mountains whose summits extend into the lightning-vulnerable spaces above treeline (Gookin, 2000; Vogt, 2014).

Extracting the spatial distribution and temporal dynamics of lightning activity is particularly important in Colorado (Fig. 1), where the largest urbanized areas, Denver and Colorado Springs, align with the state's highest lightning densities (Vogt & Hodanish, 2014), and where annually 500,000 people spend time on the highest mountain summits (CFI, 2016) and over 6 million explore National Parks and National Monuments (NPS, 2015). Despite the fact that Colorado is an interior state, its eastern and southeastern extent experience as many thunderstorm days as moisture-rich states bordering the United States Gulf Coast (MacGorman, Maier, and Rust 1984; NOAA, 2016). Colorado's highly textured and extremely variable physical landscapes generate complex, interconnected, interesting, and oftentimes surprising patterns of spatio-temporal lightning activity.

The analysis of a ten-year CG dataset by Vogt and Hodanish (2014), coupled with the contributions of earlier works that examine lightning geographies, guide the explorations herein. This article draws expertise from a Colorado-based National Weather Service (NWS) senior operational meteorologist, exploits the analytical capabilities of a geographic information system (GIS), and incorporates histograms and animations as aids for data exploration, statistical analysis, and information presentation (MacEachren et al. 2004).

The goal of this paper is to use CG lightning density (a ten year lightning climatology) as a proxy to understand relationships between thunderstorms and a set of landscape features that interact with atmospheric processes. As examples, mountain ranges, major ridges, and vast gently sloping piedmont surfaces influence atmospheric processes across Colorado. Some questions that guide the explorations include: What role does elevation play in CG lightning density? How do different configurations of mountain ranges and other physiographic features interact with thunderstorms? How does North American Monsoon (NAM) thunderstorm activity interact with mountainous topography, temporally and spatially? What topographic features help create lightning hotspots and lightning deficit regions? What is the lag time between thunderstorm initiation in high peaks versus lower elevations off to the east? Why might Colorado's interior mountain ranges experience less overall lightning, but nearly as many lightning days, as ranges closer to moisture sources? When (seasonally and daily) does thunderstorm activity peak in Colorado? In addition to the lightning/landscape explorations presented in this article, an important albeit peripheral takeaway is to recognize lightning as a hazard to those who spend time outdoors in Colorado and elsewhere.

2. Background

To better understand lightning activity in Colorado, authors have focused their investigations on select regions of the state (López & Holle, 1986; Schaaf et al., 1988) and on the state as a whole

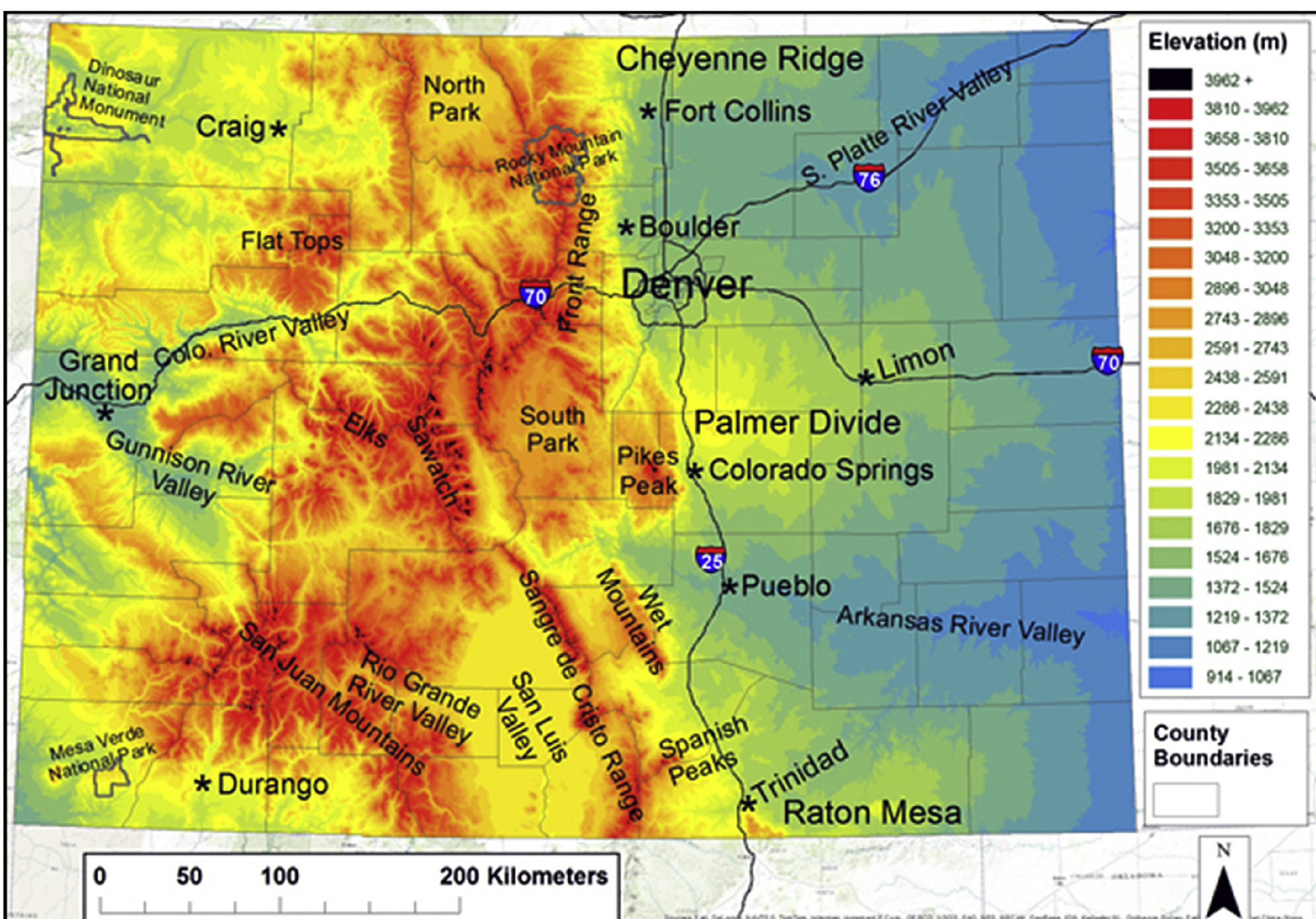

Fig. 1. Overview of the Colorado landscape. Base elevation map contour interval 152 m (500 ft). Major landscape features, populated places, two major National Parks, and a National Monument are labeled. Modified from Vogt and Hodanish (2014).

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