BAMS Article

Earth, Wind, and Fire: Are Boulder's Extreme Downslope Winds Changing?

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ABSTRACT: A Denver newspaper in 2016 reported that a new Colorado all-time record peak wind gust of 148 mph was recorded on 18 February 2016, on Monarch Pass in the Colorado Rockies near 11 000 ft above sea level. The article stated that this broke the previous record of 147 mph set on 25 January 1971 at the National Science Foundation (NSF) National Center for Atmospheric Research (NCAR) Mesa Laboratory, at an altitude of 6077 ft, on the western edge of Boulder, Colorado. Though there is no actual official peak gust record in Colorado, this raised the issue that Boulder had not recently experienced winds of the magnitude of the megadownslope windstorms that wracked the area in the 1960s, 1970s, and 1980s when extreme wind gusts recorded at the NSF NCAR Mesa Laboratory were not unusual. Due to Boulder's location at the eastern foot of a north–south mountain range (*Earth*), it is susceptible to destructive downslope winds (*wind*) often accompanied by fires (*fire*) such as the downslope wind-driven Marshall Fire just east of Boulder on 30 December 2021 that destroyed nearly 1100 homes. But after the 1990s, the weather station anemometer at NSF NCAR did not record a peak gust much over 100 mph. What changed? This detective story describes the search for causes of the apparent decrease in strength of extreme windstorms at NSF NCAR and their impacts in the Boulder area. The suspects in Boulder include a change in instrument location, changes in building codes, and increasing roughness length from tree growth. But climate change emerges as a chief culprit.

SIGNIFICANCE STATEMENT: National Science Foundation (NSF) National Center for Atmospheric Research (NCAR) was at the epicenter of megadownslope windstorms that wracked Boulder in the 1960s, 1970s, and 1980s when extreme windstorms were not unusual. But after the 1990s, the weather station anemometer at NSF NCAR, which replaced the previous anemometer that recorded the huge gusts, did not record a peak gust much over 100 mph. What changed? This detective story describes the search for causes of the apparent decrease in strength of extreme winds at NSF NCAR and their impacts in the Boulder area. Changing instrument location is part of the story, but climate change emerges as a key culprit.

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1. Introduction

A note on terminology: The National Center for Atmospheric Research (NCAR) was recently rebranded "The National Science Foundation National Center for Atmospheric Research." In the text to follow, we will use the designation "NSF National Center for Atmospheric Research" or "NSF NCAR."

A headline in the Denver Post on 19 February 2016 read "148 mph wind gust recorded Thursday on Monarch Pass" (Denver Post 2016). The article went on to report that "A blast of wind hit 148 mph on Monarch Pass Thursday, the highest gust recorded in Colorado by the National Weather Service. Thursday's Monarch Pass blast bests a previous gust of 147 mph on 25 January 1971 recorded at the National Center for Atmospheric Research in Boulder." This was an attention-getting article for a number of reasons. First, there is no official peak gust record in Colorado, and periodic studies in the 1970s and 1980s of data recorded on Longs Peak at an altitude of over 14 000 ft showed gusts up to 201 mph and numerous others above 150 mph (Glidden 1982), though there has been a debate over whether to consider the findings "official" (R. Schumacher 2024, personal communication). But what also drew attention to the article was that the epic downslope windstorms of the 1960s, 70s, and 80s, with wind gusts measured at the NSF NCAR Mesa Laboratory that routinely topped 120 mph, had seemed to have reduced in intensity over time.

Newcomers to Boulder, after reading that newspaper story, were likely surprised to learn that the Boulder area once experienced extreme wind gusts over 140 mph. For example, a headline in the Boulder newspaper after the January 1969 windstorm declared "Hurricane Force Winds Send City Reeling" with a subheadline stating "Homes Wracked; Winds Reach 130." Technically speaking, hurricane-force winds on the Saffir–Simpson scale are maximum sustained winds, not gusts, but this distinction is seldom noted when citizens of Boulder have talked about the strong downslope winds they have experienced that once produced significant property damage. But something seemed to change in the 1990s, and peak gusts measured at NSF NCAR rarely approached 100 mph after 1995.

Boulder has always been a windy place because of its orientation at the eastern foot of the north–south-oriented Rocky Mountains that present a continuous barrier to the prevailing upper-level westerlies. Boulder's strong downslope winds can be either associated with a warm wind, often referred to as a "chinook" wind and sometimes termed "prefrontal" (Mercer et al. 2008) or a katabatic downslope wind (Brinkmann 1974) sometimes termed "postfrontal" (Mercer et al. 2008). The former typically accompanies a mountain wave and is most common in winter with west-northwest flow at 500 hPa in conjunction with a surface lee trough to the east of the Rockies. The latter is associated with cold air advection after a surface cold front crosses the mountains from the west and is sometimes referred to as a "bora" which occurs near the northern coast of the Adriatic Sea. In either case, the downslope winds are a product of strong upper-level westerlies being forced over the Rockies with dynamical intensification as the winds descend from the Continental Divide down to Boulder (Durran 1990). Here, we refer to "downslope" winds that include both chinook and katabatic wind events that affect Boulder.

An early account of a downslope wind event that occurred on 17 November 1869 appeared in the 23 November 1869 edition of the Boulder County News, one of the first newspapers to be established in Boulder after the period of European settlement began in the 1850s. The article described a "heavy storm in Boulder" that blew overnight. A number of structures were "torn down or moved off their foundations" by the strong wind gusts. During the night, "different parties were up, bracing their buildings, to prevent their being blown away or broken to pieces." A large frame building on Pearl Street "was leveled to the ground entirely . . . and sundry other small structures about town were turned over, or otherwise damaged" (Whiteman and Whiteman 1974). Wind events such as this one were relatively common in Boulder's history.

Fig. 1. Position of the two anemometers atop the six-story tall A tower of the NSF NCAR Mesa Laboratory (yellow circles); contours indicate approximate westerly wind streamlines over the building, with wind flow during downslope wind events from left (west) to right (east); the photo is taken looking northwest; (left) the propeller anemometer on the mast at 10 m above roof level recorded the huge wind gusts of the windstorms of the 1960s, 70s, and 80s. (right) The WXT anemometer lower down at 2 m above roof level was installed in 1996, and after its installation there were no gusts above 100 mph recorded by this instrument (Gerald Meehl photo).

When the NSF NCAR Mesa Laboratory building was built on a mesa on the southwestern edge of Boulder in 1967, the meteorologists working there became interested in Boulder's severe downslope winds. Being inquisitive scientists, they wondered just how strong those wind gusts were, so they erected an analog anemometer atop a 10-m mast on NSF NCAR's six-story high tower A (Fig. 1).

The output of the anemometer had a readout on a strip chart, with a red pen recording wind speeds and a green pen recording wind direction. It is this anemometer that recorded the wind gust of 147 mph in 1971. But that was just one of several extreme downslope windstorms that hit Boulder in the 1960s, 1970s, and 1980s (Figs. 2a,b).

Those old strip chart recordings were not saved, but when there was a big windstorm, the local newspaper, the Boulder Daily Camera, would call NSF NCAR and ask what the peak gust was. This was much to the chagrin of the Boulder Chamber of Commerce—they did not want such severe damaging winds publicized, fearing people and businesses would not move to Boulder (D. Baumhefner 2024, personal communication). From those newspaper accounts, Catherine Smith at NOAA compiled reports of peak gusts from downslope windstorms recorded at NSF NCAR (Fig. 2a) as well as from any other source reporting measured strong wind gusts (Fig. 2b) (NOAA 2025). Figure 2c is a histogram of monthly counts of all peak gusts above 70 mph reported from any source in Boulder in Fig. 2b. Consistent with previous literature (e.g., Brinkmann 1974), there is a preponderance of strong windstorms in winter (December–February).

Though necessarily anecdotal, the extreme windstorms that produced the most damage stand out:

7–8 January 1969: peak gust of 130 mph, reports of "25 roofs blown off, heavy damage in Boulder area";
21 December 1969: peak gust of 115 mph;

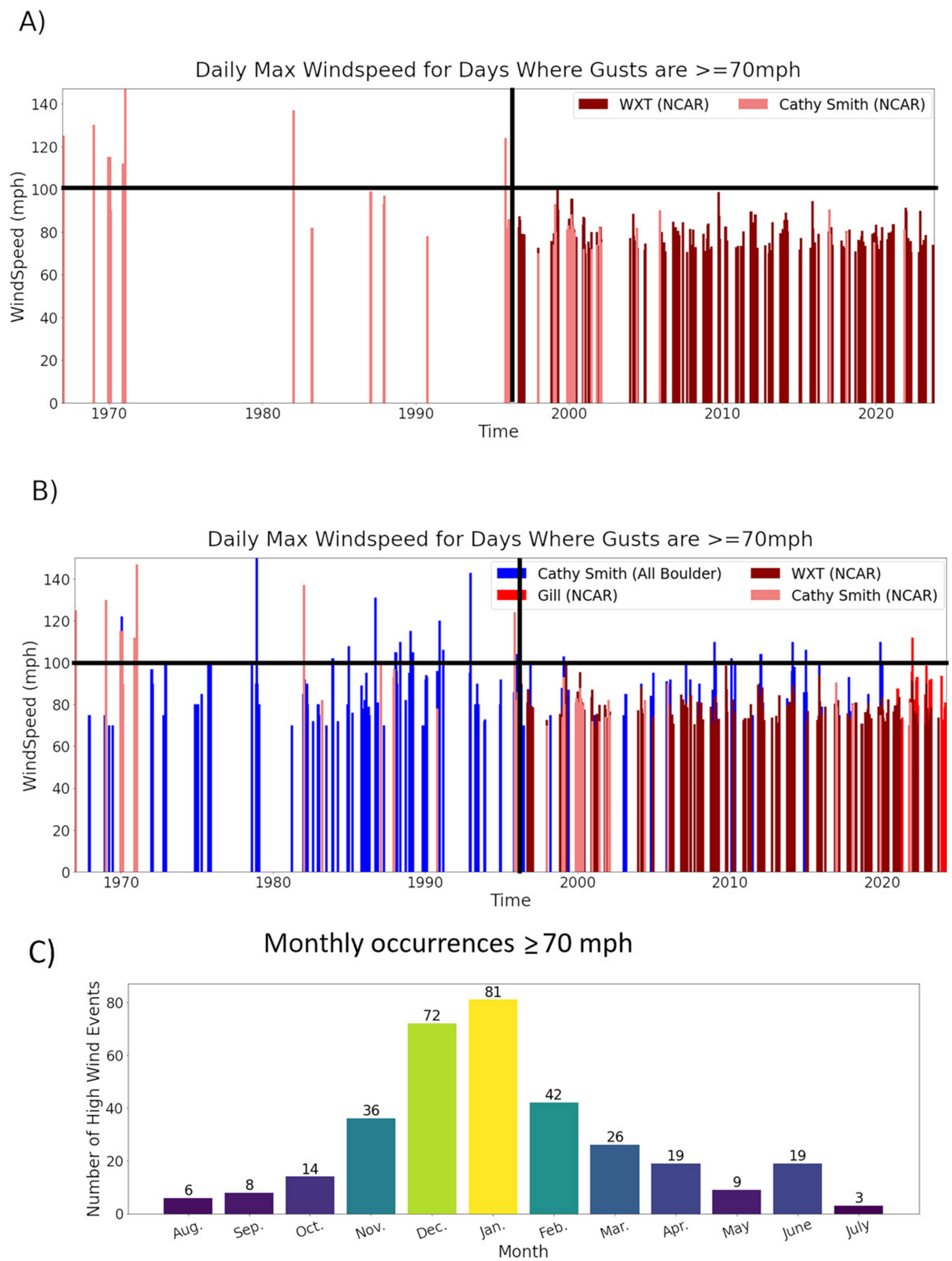

Fig. 2. (a) Time series of daily maximum wind speed for days for measured gusts greater than or equal to 70 mph for 15 Jan 1967–26 Feb 2024; Catherine Smith reports of events recorded at NSF NCAR only (light red); dark red indicates peak gusts measured by the WXT anemometer installed in 1996 atop a 2-m mast, dark horizontal line denotes 100-mph wind gusts, and dark vertical line at 1996 marks when the anemometer instruments and location on the NSF NCAR roof changed; (b) light red and dark bars as in (a), with blue bars indicating all peak gusts from anywhere in Boulder compiled by Catherine Smith; bright red bars after 2017 indicate measurements from new Gill anemometer atop the 10-m mast. Note the measurement from the Gill anemometer of 112 mph during the Marshall Fire event of 30 Dec 2021, the first peak gust over 100 mph measured at NSF NCAR since 1995; (c) histogram of monthly counts of all peak gusts above 70 mph shown in (b).

26 January 1970: peak gust of 115 mph;
3 February 1970: peak gust of 115 mph;
23 January 1971: peak gust of 147 mph;
12 December 1972: peak gust of 120 mph;
16–17 January 1982: peak gust of 137 mph.

The damage associated with those downslope windstorms was devastating, resulting in significant structural damage to homes and businesses (Fig. 3).

The November 1995 windstorm was the last peak gust well above 100 mph recorded by the propeller anemometer at 10 m above roof level at the NSF NCAR Mesa Laboratory until the installation of the Gill sonic anemometer on the mast in 2017. The propeller anemometer was disabled in 1996, and wind measurements at the NSF NCAR Mesa Laboratory were then made by the WXT sonic anemometer lower down at 2 m above roof level on the weather station that was installed in 1996. In 2017, as discussed below, a sonic Gill anemometer was mounted back atop the mast at 10 m above roof level where the original propeller anemometer was located (Fig. 1). The Gill sonic anemometer located on the taller tower is a model 75 configured to report gusts at 1-s samples (Gill 2025). The weather sensor is a WXT520 with gusts at 1-s samples (Vaisala 2012).

Therefore, in the discussions to follow, three anemometers will be discussed: the original propeller anemometer that recorded winds atop the 10-m tower from 1967 to 1996, the WXT sonic anemometer that was mounted lower down on the weather station on a mast 2 m

Fig. 3. (top left) Significant structural damage in Boulder, Colorado, from the January 1969 downslope wind event; (top right) 2 black and white photos: severe damage to the NSF NCAR aircraft hangar at Jeffco Airport (now Rocky Mountain Metropolitan Airport) from the January 1972 downslope wind event (NSF NCAR photos); (bottom right), (bottom middle), and (center left) photos of houses damaged in the Boulder Table Mesa neighborhood during the January 1972 event; (bottom left) power poles snapped off during January 1982 event on 30th Street in Boulder.

above roof level and started recording in 1996 to the present, and a Gill sonic anemometer that was installed back atop the 10-m mast in 2017 where the propeller anemometer was originally located. The Gill anemometer at the present is recording concurrently with the WXT anemometer on the weather station to compare the effects of instrument location on wind measurements (Fig. 1).

The most recent severe damaging downslope windstorm in Boulder occurred overnight on 16–17 January 1982 (Zipser and Bedard 1982). The NSF NCAR anemometer strip chart, displayed by scientist Dave Baumhefner (keeper of the weather map room and the anemometer), showed two gusts of 137 mph and numerous gusts above 120 mph (Fig. 4). There was devastating structural damage from the windstorm all over Boulder but was focused in the Table Mesa neighborhood in south Boulder below NSF NCAR (Fig. 5). Reports estimated that at least 40% of all buildings in the city of Boulder were damaged (NOAA 2025). This event was the last severe windstorm that has produced such a level of significant structural damage in Boulder to date. The November 1995 wind event with a peak gust of 124 mph was the last wind gust above 120 mph recorded at NSF NCAR but did not produce the widespread damage seen in the 1982 event.

The apparent decrease in severity of windstorms in the Boulder area moved downslope wind events out of the consciousness of most Boulder residents until 30 December 2021 when downslope winds approaching 100 mph east of Boulder (and a measured gust of 112 mph measured on the Gill sonic anemometer at NSF NCAR; Fig. 11) combined with extremely dry conditions to drive a wildfire into neighborhoods just east of Boulder

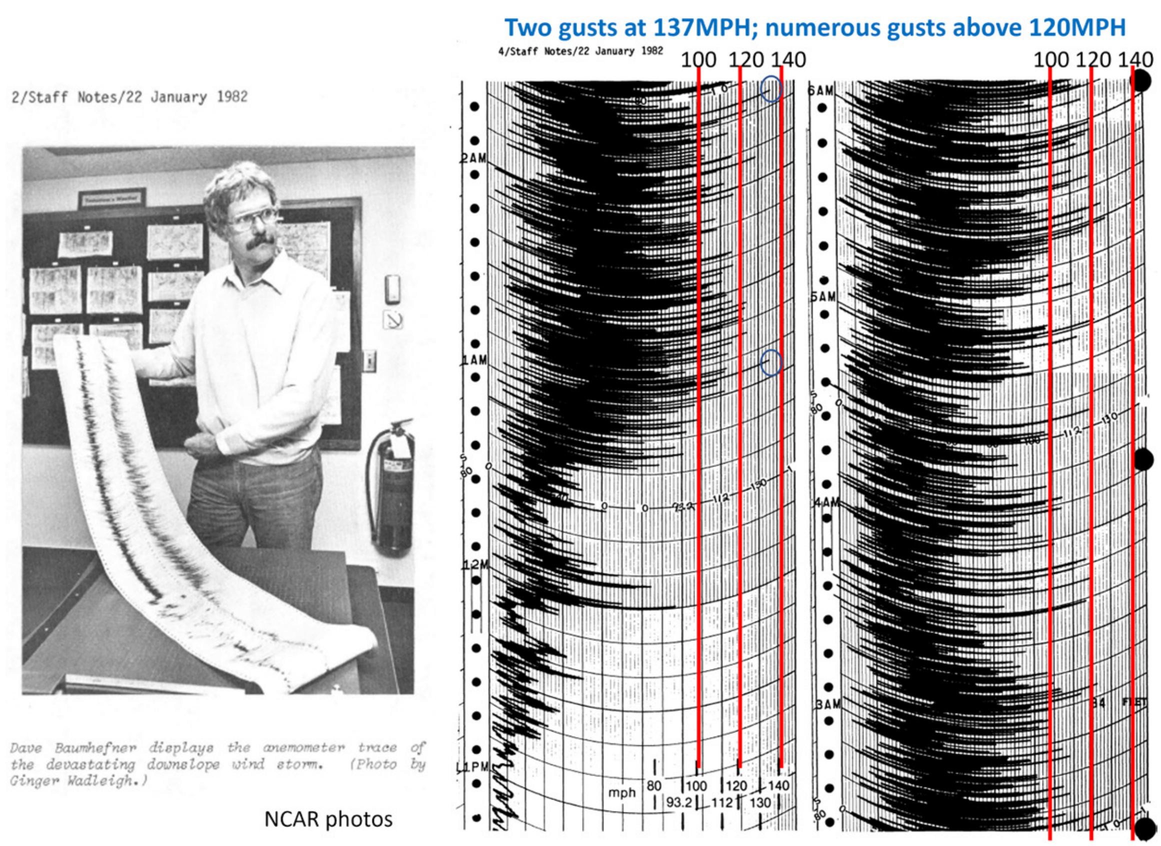

Fig. 4. **(left) Dave Baumhefner with the anemometer trace in the NSF NCAR Mesa Laboratory weather map room after the January 1982 downslope wind event (NSF NCAR photo); (right) NSF NCAR Mesa Laboratory wind speed anemometer trace (black line) from the January 1982 downslope wind event showing two gusts at 137 mph and multiple gusts above 120 mph (red vertical lines denote wind speeds of 100, 120, and 130 mph). (center) Time begins at the bottom near 2300 LT and increases upward to after 0200 LT. (right) At the bottom after 0200 LT, with time increasing upward until 0600 LT when gusts above 120 mph were still being recorded. Gusts above 120 mph occurred from about 0100 LT until after 0600 LT, a period of extremely strong winds of over 5 h (NSF NCAR photo).**

Fig. 5. Wind damage from the January 1982 downslope wind event in Boulder, Colorado, when the NSF NCAR anemometer recorded two 137-mph gusts and numerous gusts above 120 mph. (top left) The roof of the house blew off, was airborne, and flew over (top right) the house next door only to crash two houses down to cause damage. (bottom left) House across from Bear Creek Elementary School was blown apart. (bottom right) Photo: damage to a house and vehicles on Lehigh Drive (Gerald Meehl photos).

(Fovell et al. 2022; Benjamin et al. 2023). The resulting firestorm destroyed nearly 1100 homes, damaged many more, and became the most damaging wildfire in Colorado history (Fig. 6). Many residents who had just recently moved into the Boulder area found it hard to believe that not only could such strong winds occur but also could combine with fire to produce that kind of devastation. History shows that the wind gusts of 30 December 2021 did not come close to the 147 mph event in 1971 or even the 137 mph windstorm of 1982. Yet, when combined with fire, nearly any strong wind can become devastating. For example, Abatzoglou et al. (2023) note that most structure losses and fatalities in western U.S. fires (1999–2020) have occurred during downslope wind events.

In fact, fire has always been part of the downslope wind equation in Boulder, as in other downslope wind regimes across the western United States as noted above (Abatzoglou et al. 2023). From a survey of historical media reports in Boulder from the 1860s to early 1970s, Whiteman and Whiteman (1974) concluded “Fires occur frequently during Boulder’s windstorms and are often difficult to control under the high wind conditions. Fires have been reported in 57 out of the 151 windstorms (that were surveyed up to the early 1970s). Common causes of fires include broken power lines, spark-ignited fuel, and windblown ashes.” Their text, written in 1974, is eerily prophetic of the 2021 Marshall Fire that had those same ignition factors. An example from their exhaustive accounting of severe downslope wind events in Boulder is the following entry that reported fires in the Marshall area east of Boulder associated with a “high wind” event with damage in Boulder:

> “Date: 2 January 1936; time: **late afternoon fires** 1730–1830 LT; area: Boulder, Marshall; damage (Boulder only): widespread; velocity: high wind.”

Fig. 6. (left) Time sequence of the 30 Dec 2021 downslope wind event that drove the Marshall Fire into subdivisions just east of Boulder, taken from a webcam in the town of Superior (https://boulderflatironcam.com/superiorcam/); note foehn wall (wall cloud) covering the Continental Divide, a typical feature of downslope wind events (see text and Figs. 7 and 9); (right) the wind-driven Marshall Fire burning into the towns of Superior and Louisville just east of Boulder (top-right photo: https://www.du.edu/news/qa-trauma-aftermath-marshall-fire; bottom-right photo: https://www.denverpost.com/2021/12/30/boulder-county-wildfire-marshall-fire-photos/).

Once again, this event in 1936 foreshadowed the Marshall Fire that was associated with strong downslope winds in 2021. But in 1936, there were no large subdivisions near Marshall that could burn as they did in the urban firestorm of 2021. The 2021 Marshall Fire claimed three lives (two people were killed in the fire and one person was killed rebuilding a home lost to the fire; NineNews 2023). Whiteman and Whiteman also report that a number of fatalities have occurred in conjunction with earlier windstorms. One of those was related to the 1969 downslope windstorm when a fireman died after being blown off the back of a fire truck that was racing to fight a wind-driven fire (Whiteman and Whiteman 1974).

2. Ingredients of a severe downslope wind event

The elements that make up a severe downslope wind event have been well known since at least the 1970s when there was a burst of research in analyzing observations and in modeling such phenomena (Lilly and Zipser 1972; Klemp and Lilly 1975). Most severe downslope windstorms occur in winter when the westerlies are strongest but can also occur in fall and spring (Brinkmann 1974; Fig. 2c). Such events usually have strong northwesterly or westerly winds around 500 hPa over Colorado, high surface pressure to the west of the Continental

Divide, a lee-slope trough that contributes to the consequent strong surface pressure gradient, and a lower troposphere inversion just above the mountain top level (Durran 1986) (Fig. 7). These conditions can then set up a mountain wave that accelerates the flow as the air descends in the lee of the Continental Divide (Fig. 8).

At the trough of the wave, surface winds can become extreme, and Boulder sits right at the position of those strongest winds. As the flow continues eastward, there is a hydraulic jump just to the east of Boulder that shoots the winds upward, thus shutting off the strongest winds just to the east of the jump [Fig. 8; see Durran (1990), for a more complete discussion of a hydraulic jump]. Sometimes, a rotor [a low-level vortex with a horizontal axis parallel to the mountain wave with winds rotating clockwise in the vertical plane; see Doyle and Durran (2002) for a discussion of rotor dynamics] forms to the east of the

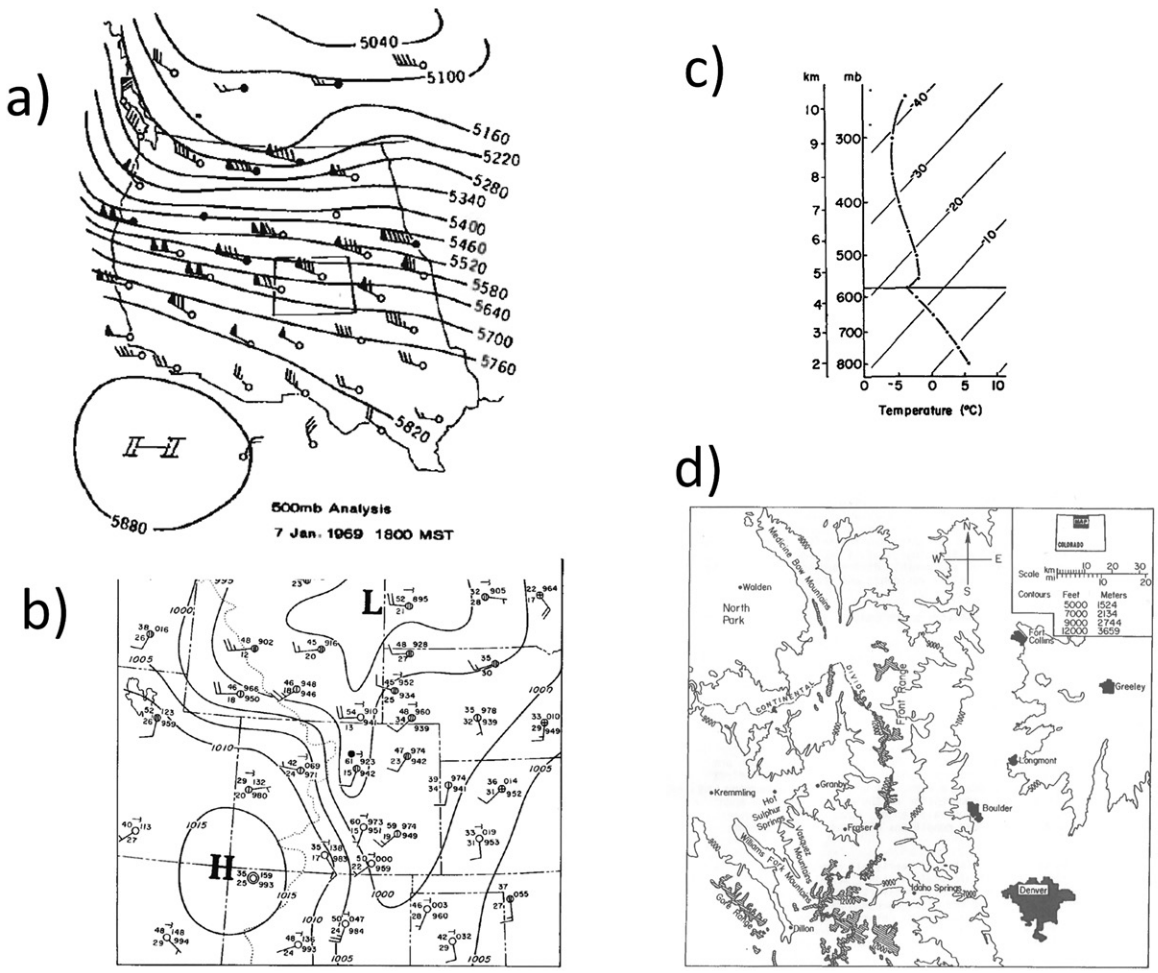

Fig. 7. Plots from early classic papers describing severe downslope winds; (a) 500-hPa heights (contours) and 500-hPa winds from stations for the January 1969 downslope wind event, showing strong W-NW winds over Colorado; triangular wind barbs are 50 kt (1 kt ≈ 0.51 m s⁻¹), a single linear barb is 10 kt, and a half barb indicates 5 kt (Whiteman and Whiteman 1974); (b) station data and sea level pressure contours for the January 1969 downslope wind event (Julian and Julian 1969); (c) composite mean upwind sounding chosen based on optimum wind speed/direction from soundings at upwind stations at Grand Junction, Colorado; Lander, Wyoming; and Salt Lake City, Utah, for the time close to the start of 20 downslope windstorms in Boulder; before averaging, the soundings were vertically adjusted so that the level average lies at the inversion bases of all events at about 580 hPa, where the mountain-top level is about 650 hPa (Brinkmann 1974); (d) topography west of Boulder showing the Continental Divide (dashed–dotted line) presenting a continuous north–south barrier from near Fort Collins to well south of Denver (Whiteman and Whiteman 1974). Also, note the farthest eastward extent of the Continental Divide lies just to the west of Boulder, presenting a unique topographic arrangement in the Front Range region.

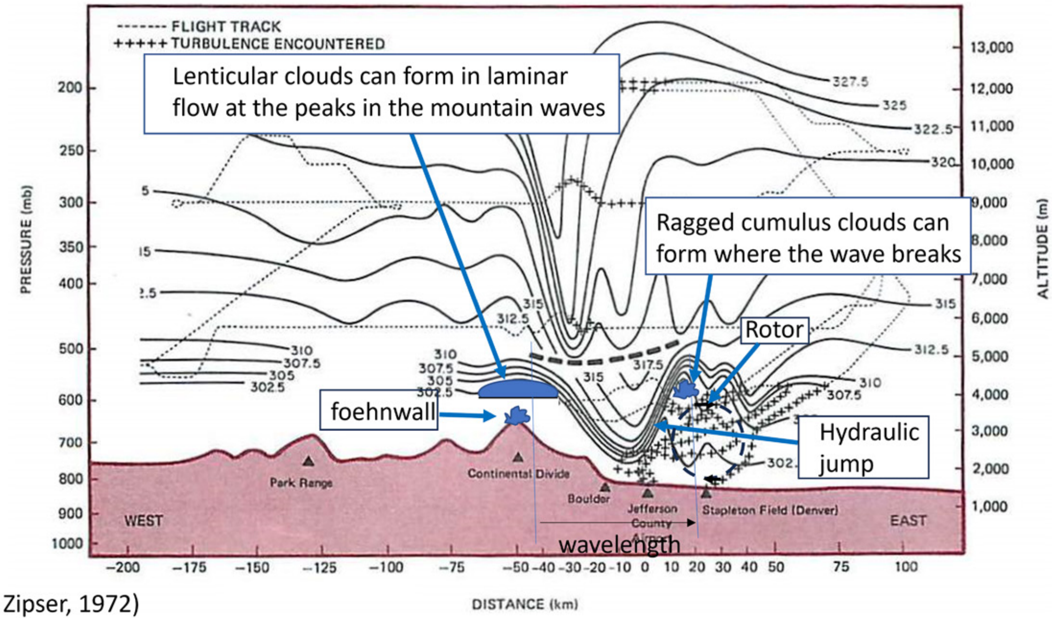

Fig. 8. The vertical structure of a severe downslope wind event that occurred in January 1972; contours of potential temperature are suggestive of wind flow along an east–west line through Boulder; data are derived from NSF NCAR research aircraft flights during the event (after Lilly and Zipser 1972). Position of the foehn wall over the Continental Divide, lenticular clouds that can form at the crest of the mountain wave, the hydraulic jump east of Boulder, an implied rotor circulation (light dashed line) just to the east of the hydraulic jump, and cumulus clouds that can form where the wave breaks at the top of the hydraulic jump are noted. Observations in the region below the heavy dashed line were taken at least 2 h before those above. It is likely that the westward displacement of the mountain wave aloft is due to the difference in the time of the flights used to obtain these data (Lilly and Zipser 1972). Most probably, the wave would be more in phase though still with a westward tilt in the vertical (e.g., Durran 1990). The relative warmth of downslope winds in Boulder is illustrated by the transport of higher potential temperature air downward within the mountain wave.

hydraulic jump, producing easterlies at the surface and a prevalence of severe turbulence east of the hydraulic jump with implications for aviation (Fig. 8) and even wind damage (Zipser and Bedard 1982). A hydraulic jump with ragged cumulus clouds at the top as in Fig. 8 can be captured visually if there is blowing dust (as in the Sierra Wave Project in the early 1950s that studied the downslope winds in the lee of the Sierra Nevada; Fig. 9a) or the smoke from the Marshall Fire in 2021 (Fig. 9b). An instructive visual example of a hydraulic jump is a surfer riding one in the lee of water flowing over an obstruction (Fig. 9c). It has been suggested that a weak rotor rotating counterclockwise in the cross section (when looking north) can form to the west of the hydraulic jump as indicated by the cumulus clouds at the top of the jump extending to the west as seen in Fig. 9b (Fovell et al. 2022; Benjamin et al. 2023).

As the westerly flow aloft is forced up and over the Continental Divide, the air cools and condenses into a cloud, called a foehn wall, or wall cloud, that caps the divide. When seen from Boulder, a typical foehn wall looks like a bank of stationary clouds sitting over the divide. In reality, there is air moving continuously through the cloud, forming the cloud on the western edge and dissipating the cloud on the eastern edge (Fig. 10). A feature of such mountain waves is that they can propagate vertically, with evidence of the wave extending to the upper troposphere (Fig. 8; and, e.g., Klemp and Lilly 1975). At the apex of the upper-level wave, lenticular clouds can form and often produce spectacular sunsets in Boulder (Fig. 10). At the crest of the hydraulic jump to the east, ragged cumulus clouds can form to mark the eastward extent of the strong surface winds (Fig. 9a).

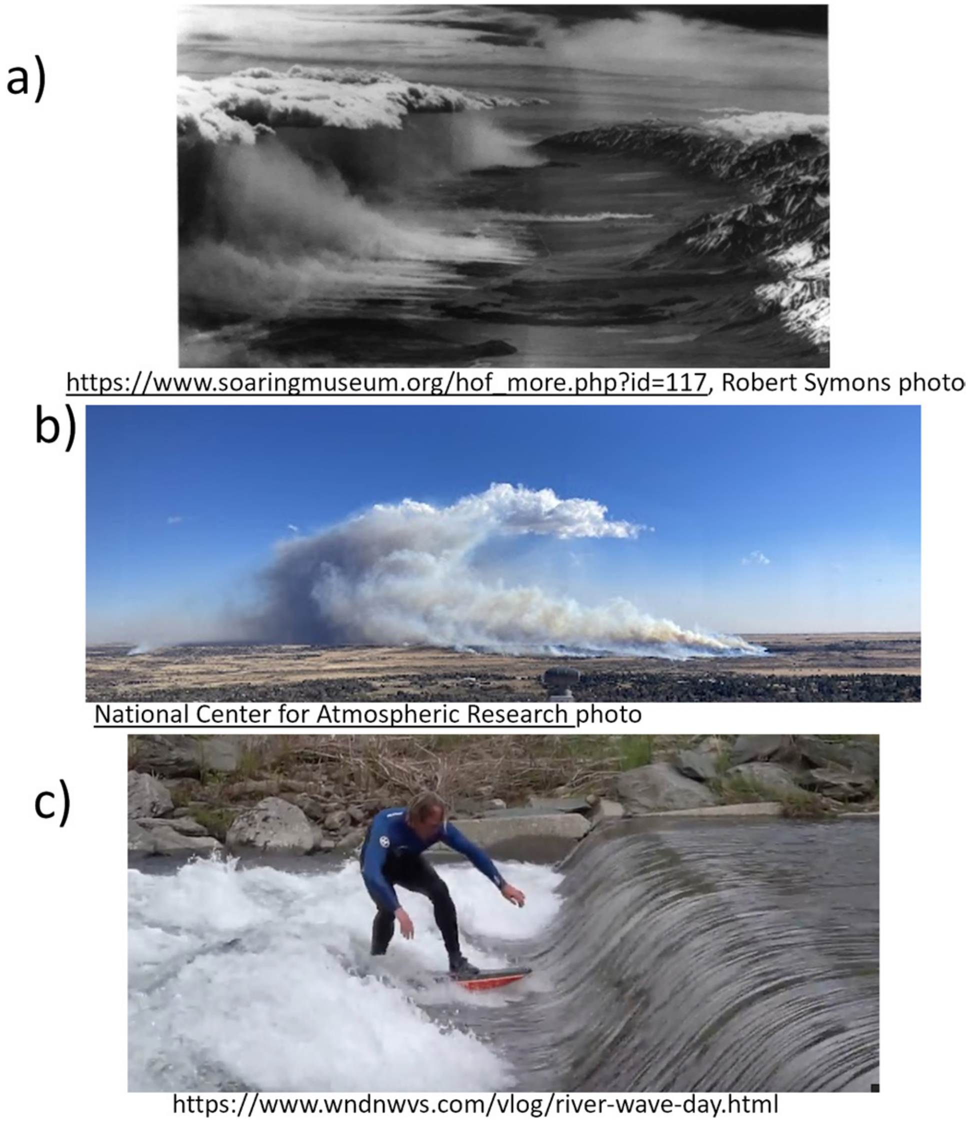

Fig. 9. (a) Cumulus clouds can form at the top of the hydraulic jump where the mountain wave breaks and can be traced from blowing dust in the Owens Valley in the lee of the Sierra Mountains from a downslope wind event during the Sierra Wave Project in the early 1950s, wind flow from right to left (https://www.soaringmuseum.org/hof_more.php?id=117; Robert Symons photo); (b) photo taken from NSF NCAR Mesa Laboratory looking southeast at the Marshall Fire during the downslope wind event of 30 Dec 2021; wind flow from right to left; smoke from the fire traces the hydraulic jump with the breaking wave-forming cumulus clouds at the top (NSF NCAR photo); (c) surfing on a hydraulic jump from water flowing over an obstacle, with white water at the top of the jump behind the surfer where the wave is breaking (photo: https://www.wndnwvs.com/vlog/river-wave-day.html).

3. Have peak gusts in Boulder's downslope windstorms decreased?

There are a number of factors that could produce either a real or apparent decrease of peak wind gusts and associated wind damage in Boulder after the 1990s. These possibilities include the following:

1) The gusts are as strong as they always were, but there is less wind damage due to more restrictive building codes in Boulder;
2) The wind damage in Boulder is less because the trees have grown larger over the last 40 years, thus increasing roughness length and reducing the magnitude of gusts at the surface, or the pine trees around NSF NCAR are taller and perhaps exert some kind of influence on the measurements;

Gerald Meehl photos

Fig. 10. (top) Foehn wall (wall cloud) over the Continental Divide west of Boulder during a downslope wind event (Gerald Meehl photo); (bottom) lenticular clouds forming at the top of a mountain wave taken from Boulder (Gerald Meehl photo).

3) The gusts have not decreased in intensity, but the movement of the anemometer position (and/or change in instrument) at NSF NCAR has resulted in a decrease in measured magnitude;
4) The peak gusts have actually decreased in strength due to climate change.

We will discuss each of these in turn.

a. Building codes. After the severe structural damage from the Boulder windstorms of the 1960s and 70s, Boulder did indeed strengthen its building codes to harden structures to better resist wind damage, but it took a while for this to happen. Even after the extensive structural damage from the windstorms of the 60s and 70s, the 1970 and 1976 City of Boulder Building codes were unchanged from the 1961 version and did not have any local amendments (Kee and Moors 2018). Finally, in 1979, the code was amended to require prescriptive strapping and uplift connections between the roof and wall framing. Prescriptive strapping by this definition connects all components of framing systems (roof, deck, load bearing walls, floor framing, etc.). Uplift connectors protect buildings from upward forces and help prevent roofs from being blown off (Boulder County Assessor 2025). The details of this change in the building code are found in section 1507.2.8.1: "High wind attachment. Underlayment applied in areas subject to high winds . . . greater than 110 mph (49 m s^{-1}) . . . shall be applied with corrosion-resistant fasteners in accordance with the manufacturer's instructions. Fasteners are to be applied along the overlap at a maximum spacing of 36 in. (914 mm) on center" (City of Boulder 2025). Of course, this change to the building codes applies only to new construction, so it takes a while for a significant number of new buildings to have these construction elements that would help reduce overall wind damage. If it took from 1979 to the late 1990s for these changes to really make a difference, then perhaps the wind gusts were just as strong as before the new building codes were established but produced less wind damage after the 1990s (Kee and Moors 2018).

b. Taller trees and increased roughness length. A quick look at photos taken of Boulder in the 1970s and after the 1990s shows the trees that were planted during Boulder's building boom of the 1960s underwent considerable growth in that 20-yr period. This was particularly true in the south Boulder Table Mesa neighborhood which always seemed to be slammed by the strongest winds and endure the worst damage. Bigger trees mean increased roughness length which could, in theory, reduce wind speed near the surface. With tree growth over the decades, there also is an effective vertical displacement of the "surface layer." Many of the trees in Table Mesa are evergreen and could have slightly decreased wind speed even in wintertime as they have grown. Additionally, the pine trees near the NSF NCAR building have grown taller during this period and could somehow have affected the wind measurements, though they are still well below the height of the anemometers on the roof. However, these factors cannot be ruled out until we look at other sources that could have produced lower magnitude measurements of peak gusts.

c. Change in anemometer location. There was a significant change of position of the anemometer on NSF NCAR's roof that occurred in 1996, along with a change from a propeller anemometer to a sonic instrument, the WXT anemometer, suspiciously coincident with the reduction in measured peak gusts. At that time, the automatic weather station that was installed on the roof reported meteorological measurements, including 5-min average wind speeds and peak gusts, to a website that could (and still can) be publicly accessed (NCAR 2025). But the WXT anemometer on the weather station was on the top of a 2-m mast above the roof and located farther east compared to the original propeller anemometer that was atop a 10-m mast above the roof farther to the west (Fig. 1). Thus, the new weather station WXT anemometer was more sheltered from the strong winds with a prevailing direction from the west. The original propeller anemometer, dating to the 1960s, was located higher up and could conceivably measure stronger winds less disturbed by airflow disruptions as the wind blew over the top of the building. When the new weather station WXT anemometer was installed on the roof in 1996 and the old propeller anemometer was still reporting, NSF NCAR scientists noticed a decrease in recorded wind peak gusts measured by the new WXT anemometer, but there was no systematic study to determine how much the peak gusts decreased with the new anemometer location. An additional caveat is that there could be some differences in measured wind speeds due to the different technologies (propeller vs sonic, e.g., Laboratori di Strumentazione Industriale 2025), though these differences are likely smaller than the effects in change in position as noted in the analysis below.

To quantify the effects of instrument and instrument location, in 2017, a new digital sonic anemometer (Gill) was installed atop the old 10-m tower where the original propeller anemometer, which recorded the big windstorm gusts prior to the late 1990s, was located. Now, a comparison could be made with the wind measurements from the two anemometers (with the caveat that even though both use sonic technology, they are not exactly the same instrument). As expected, the anemometer atop the 10-m mast located farther west on the NSF NCAR roof measures higher peak gusts (Fig. 11). A comparison during the 3-yr period of 2021–23 shows that the top 1% of wind gusts measured by the Gill anemometer atop the 10-m mast (in the location of the pre-1990s propeller anemometer) compared to the WXT anemometer lower down on the weather station (Fig. 11a) are about 10% stronger. When comparing the top 0.1% of wind gusts observed at the NSF NCAR Mesa Laboratory, mean peak gusts are 16% stronger with the Gill anemometer than with the WXT anemometer (Fig. 11b). Therefore, there was a reduction of measured peak gusts after 1996 just due to the movement of the anemometer location. These measurements, both made with sonic anemometers (though as noted earlier somewhat different sonic technology for each), suggest that the change in the instrument from the propeller to sonic made less of a difference than the change in location.

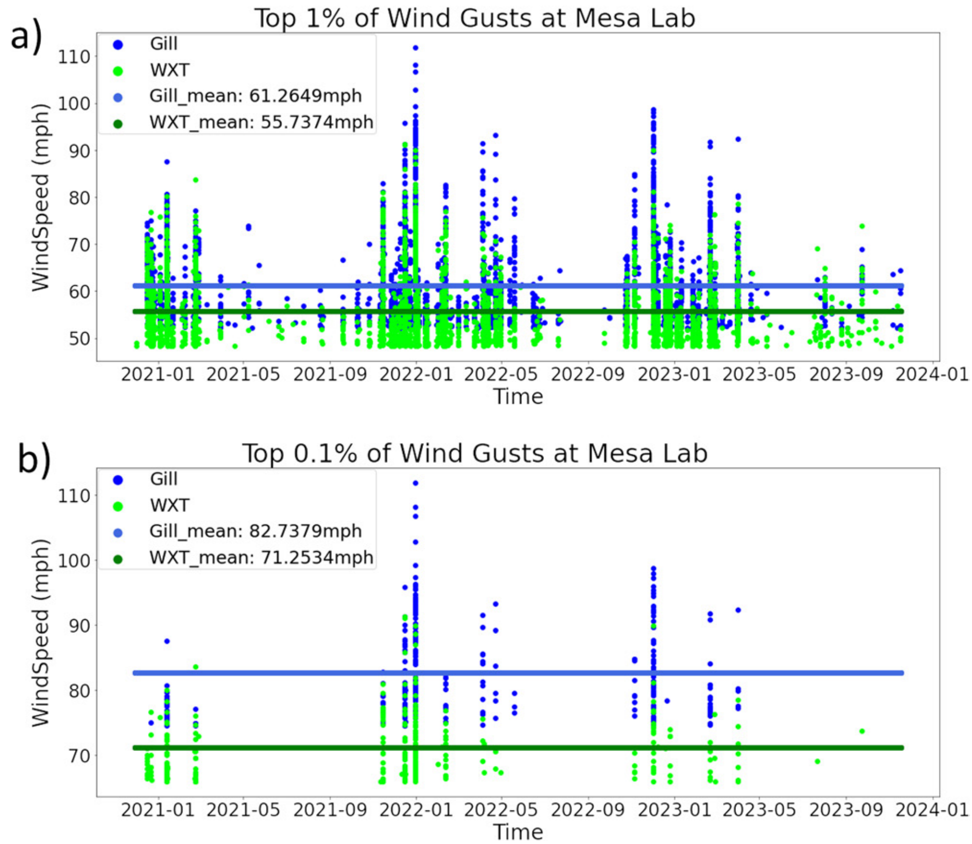

Fig. 11. Example of the time series comparison of the two NSF NCAR Mesa Laboratory anemometers for (a) the top 1% of wind gusts from 2021 to 2023 and (b) top 0.1% of wind gusts; blue dots are the Gill sonic anemometer atop the 10-m mast; green dots are the WXT sonic anemometer on the weather station lower down and farther east on the roof; solid horizontal blue line is average peak gusts for the Gill anemometer; solid horizontal green line is average peak gusts for the WXT anemometer; and there are consistently stronger peak gusts from the Gill anemometer atop the mast. The peak gust of 112 mph measured by the Gill anemometer during the 30 Dec 2021 downslope wind event and consequent Marshall Fire (compared to a peak gust near 90 mph from the WXT anemometer) was the first significant wind gust well above 100 mph recorded at NSF NCAR since the previous anemometer on the mast was decommissioned and the WXT weather station anemometer was installed in September 1996.

Wind roses compiled from the WXT and Gill anemometers show a reduction in peak gusts, with the Gill anemometer atop the 10-m mast showing stronger peak wind gusts (top 1% and top 0.1%) from west-southwest (W-SW) (Fig. 12). The WXT anemometer lower down on the weather station shows somewhat weaker peak wind gusts (fewer yellow colors) from a bit more westerly direction. Alignment of the anemometers was checked, and an 11.7° correction toward the east of true north was applied prior to the Gill data being plotted in Fig. 12. We speculate that the slight direction difference between the peak gusts from each anemometer likely receives contributions from the aerodynamic properties of the wind flow over the NSF NCAR tower that affect both wind strength and direction. However, making a quantitative attribution for those direction differences is beyond the scope of our present study.

If the more recent wind gusts measured by the WXT weather station anemometer were corrected to be comparable to the wind gusts measured atop the tower, would the post-1996 wind gusts be more consistent with pre-1996 peak gusts? A correction of 10% for the top 1% of gusts and 16% for the top 0.1% of gusts can be applied to peak gusts for windstorms after the late-1990s from the WXT anemometer (Fig. 2). Even with the largest measurement adjustment of 16% for the top 0.1% of gusts, the strongest post-1996 gusts of 100 mph corrected to 116 mph still lie well below the big wind events in the pre-1996 period when there were seven windstorms with gusts well above 117 mph, with four events above 120 mph. Note that in

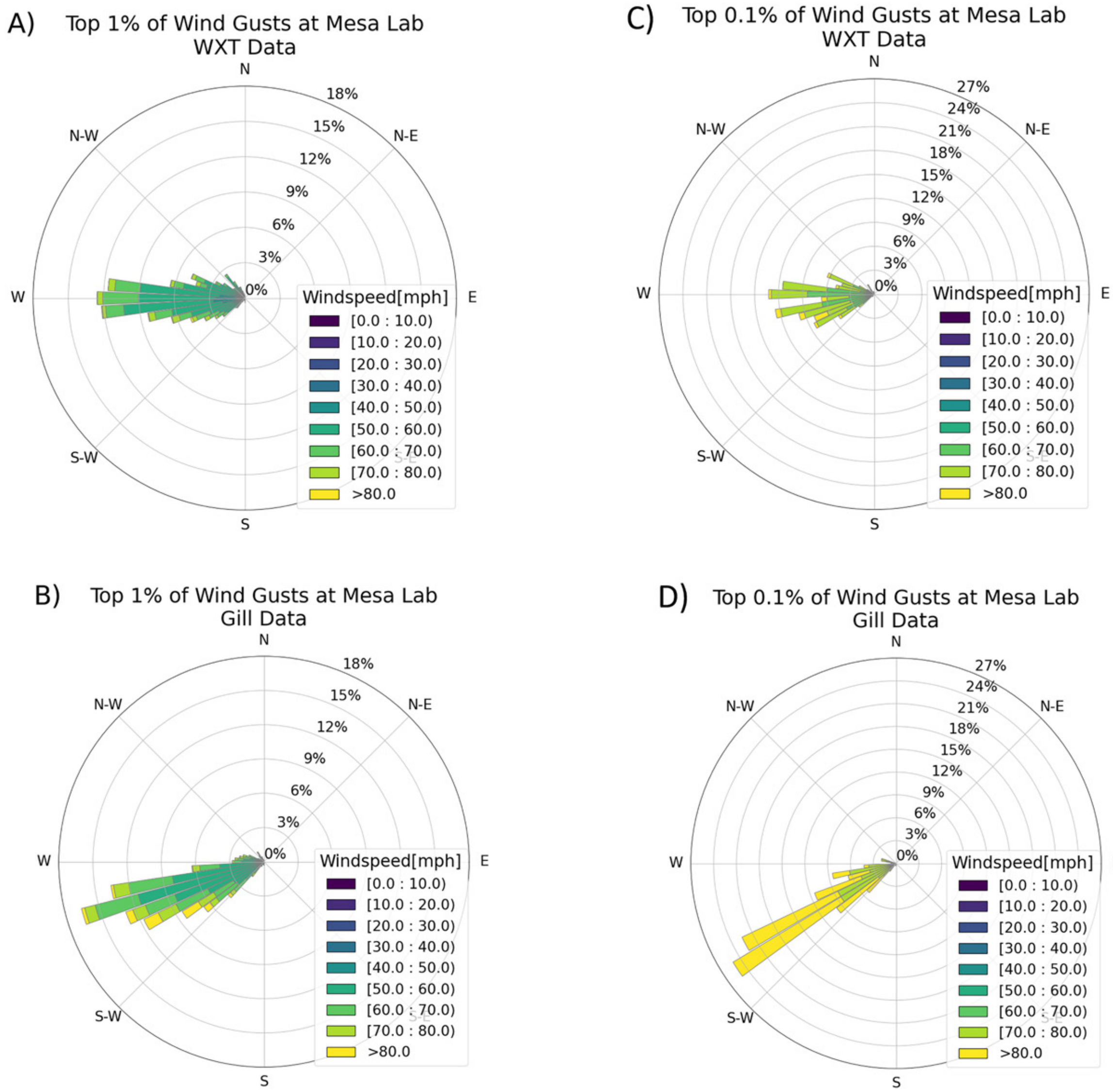

Fig. 12. Wind roses for the top 1% of wind gusts from (a) the WXT anemometer lower down on the weather station; (b) the Gill anemometer atop the mast; (c) as in (a), but for top 0.1%; and (d) as in (b), but for top 0.1%.

Catherine Smith's compilation (Fig. 2), she reported other peak gusts in south Boulder that approached 110 mph after 1996, but those were from private citizens reporting gusts to the newspaper, and their reliability cannot be verified. Therefore, the reduction of peak gusts after the 1990s measured at NSF NCAR cannot be explained only by changes in the siting and type of anemometer used, with the caveat that the propeller anemometer could have actually measured peak gusts more accurately. However, the evidence from the comparison between the two sonic anemometers argues for an actual reduction in peak gusts during the more recent period.

It should be noted that this is just one measurement from a single location. Is this observation representative of a larger scale change in strong wind gusts across the Colorado Front Range? There are other anemometers measuring winds in the Front Range area that are compiled in the NOAA Storm Reports (NOAA 2024). Those measurements only extend back to the mid-1990s which is about the time that peak gusts were noted to decrease at NSF NCAR. However, it is useful to look at these available records to see if there is any evidence that strong wind events have decreased since the mid-1990s in an area that extends beyond Boulder. There are a number of ways to compile these events, and the authors encourage the reader to take a look at the web page to confirm our compilations that show a secular reduction in the number of events with strongest gusts above 70 mph from the mid-1990s to the present from the reports from Boulder County, as well as from the Front Range counties also in the lee of the Rockies affected by downslope winds: Larimer County to the north and Jefferson County to the south.

Thus, in the period when NSF NCAR winds were weakening compared to the earlier period, there are indications of a reduction of the strongest wind events since the mid-1990s across these three counties.

d. Large-scale conditions associated with reductions in post-1990s peak gusts along the Front Range. As noted above, there is evidence that there has been a reduction in the strength of peak wind gusts at NSF NCAR, but is there any evidence for changes in the vertical wind structure during severe windstorms after the 1990s or wind speed changes in a larger Front Range region? Figure 13 shows the average vertical wind structure for strong wind events in cross sections at the latitude of Boulder (40°N). Composites are formed from the reported strong wind events above 70 mph in Fig. 2b for two epochs, an earlier period 1967–93 (138 events; Fig. 13a) and a more recent period 1995–2021 (121 events; Fig. 13b). The procedure is to start by taking a strong wind event in Boulder on a given day with a gust above 70 mph in Fig. 2b, then look at all hourly data in reanalyses [the fifth major global reanalysis produced by ECMWF (ERA5); Hersbach 2023] from that day, pick the hour that had the strongest wind value, and save that value for that day and that hour for the composite. These hourly averages will not necessarily reflect the peak gust magnitudes in Fig. 2b but should represent contrasts in hourly mean conditions during strong peak gust events in the two epochs. The strong wind composites for the earlier period (Fig. 13a) show wind magnitudes nearly twice as strong as the more recent period (Fig. 13b) at nearly all levels (standard deviations are comparable in magnitude to the composite winds).

To examine the geographical distributions of wind changes, differences between these two epochs for strongest 700-hPa winds in the lower troposphere (700 hPa in ERA5 using hourly data) show large-scale reductions of wind speeds east of the Rockies in the more recent period during extreme wind events (Fig. 13c). This is consistent with the reductions in the strongest wind gusts in Boulder and at NSF NCAR (Figs. 2a,b). There are mean reductions in wind strength of over 5 mph along the Front Range in the recent period (Fig. 13c; hourly standard deviations of winds in the lee of the Rockies for the recent period are about 5 mph). Though the relatively small number of samples precludes assessment of statistical significance, this result provides qualitative consistency with the weakening of wind gusts observed after the 1990s at NSF NCAR. This indicates that there likely have been reductions in wind speeds during strong wind events not only in the vertical but also across the broader Front Range region in the more recent period compared to the earlier period.

To relate these changes in strong gusts to mean DJF climatological differences in 500-hPa winds between the two periods, Fig. 14a shows positive differences indicating stronger mean winds at 500 hPa in the more recent period, compared to weaker mean winds at 700 hPa in the lee of the Rockies (Fig. 14b) of more than −4 mph (interannual DJF standard deviations are about 5 mph). This indicates a change in DJF base-state climate with an increase in vertical wind shear in the more recent period that could have contributed to the decrease in peak gust magnitude.

In terms of how these regional climatological wind changes in Fig. 14 relate to differences in the vertical structure of temperature and wind between the two epochs, a cross section taken at the latitude of Boulder (40°N) in Fig. 15a shows mean increases of temperature greater than +0.5°C above 500 hPa and increases of only about +0.2°C near 700 hPa. This is indicative of an upward shift in lower-tropospheric vertical temperature gradient (interannual DJF standard deviations around 0.8°C). Figure 15b shows mean decreases of zonal wind speed

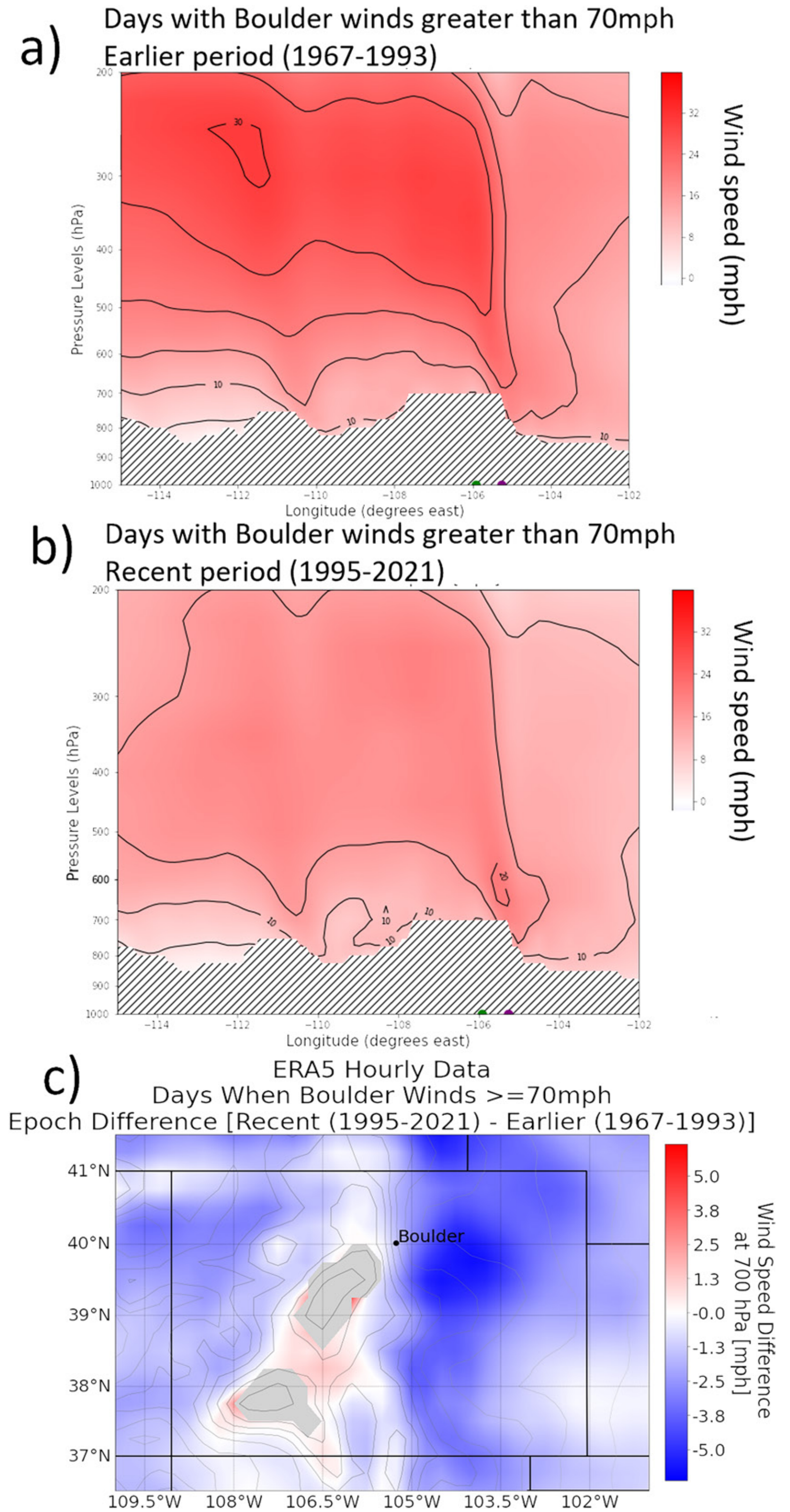

Fig. 13. (a) Vertical cross section of observed ERA5 (Hersbach 2023) mean winds (mph) at the latitude of Boulder (40°N) from (left) western Colorado to (right) east of Boulder during downslope wind events with gusts greater than or equal to 70 mph (from Fig. 2b) for the earlier period (1967–93); (b) as in (a), but for the recent period (1995–2001); (c) observed epoch differences in 700-hPa winds (mph) during downslope wind events with gusts greater than or equal to 70 mph (from Fig. 2b) for the recent period (1995–2001) minus the earlier period (1967–93) from the ERA5 reanalysis; weaker winds in the more recent period are indicated by blue colors. The ERA5 data have 0.25° horizontal resolution, so the representation of topography (thin contours) is necessarily smoothed. See Fig. 7d for a more accurate depiction of topography showing the Continental Divide as a continuous barrier stretching from northern to southern Colorado.

of more than −1 mph in the lee of the Rockies near 700 hPa (interannual DJF zonal wind standard deviations between 1 and 2 mph near 700 hPa) and increases of wind speed approaching +1 mph near 500 hPa (interannual DJF standard deviations of around 4–5 mph), consistent with Fig. 14. The anomalies are not large, but this change in the background base-state climate indicates a mean increase in vertical wind shear that has been documented as a trend associated with global warming [e.g., Woolings et al. (2023), for about 35°–50°N from 1979 to 2019 in ERA5 reanalyses; Shaw and Miyawaki (2024), for nearly all latitudes for future climate from the CMIP6 simulations].

Whether or not these epoch changes in the background base states are producing the observed weaker windstorms in Boulder is an intriguing science question, but it is beyond the scope of the present paper. One issue involved with interpreting the climatological changes in Fig. 15 is how much is a cause of weakened peak gusts and how much is an effect of weakened peak gusts. But the upward shift of static stability implied by larger warming in the midtroposphere (Fig. 15a) could imply a weakened mountain-top inversion that was noted earlier to be an ingredient in producing strong downslope winds and thus could contribute to weakened mountain waves in the more recent period. Additionally, increases in vertical wind shear, like those in Fig. 15b, have been shown to decrease mountain-wave formation in a model sensitivity study by Fovell et al. (2022) and thus also could be a factor. However, this is speculation at this point and will be the subject of a follow-up study that will use the Weather Research and Forecasting (WRF) Model to simulate case studies of severe downslope wind events to quantify factors that could be contributing to secular changes in peak gusts in Boulder and the surrounding Front Range region.

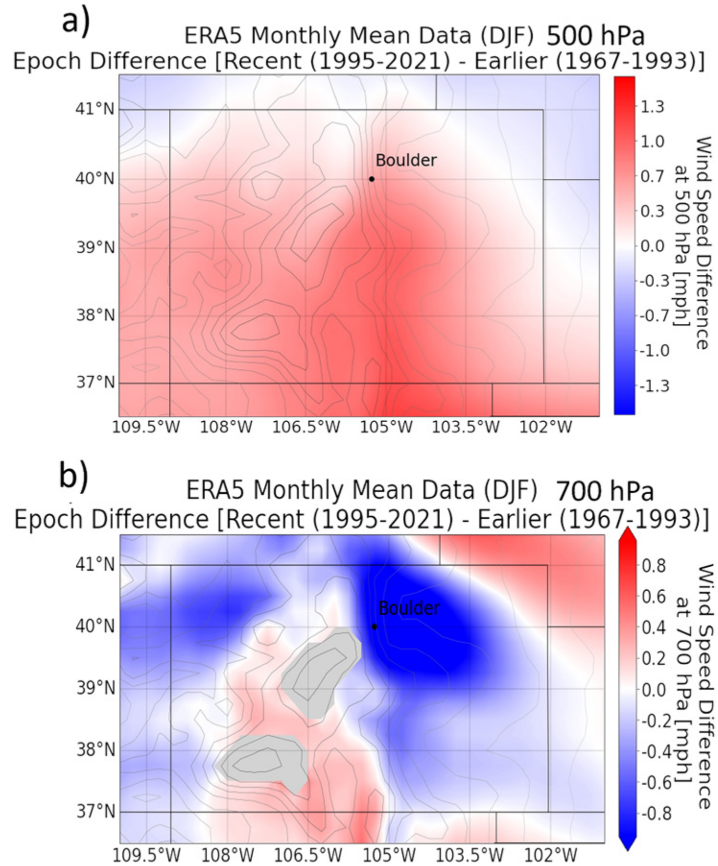

Fig. 14. (a) Observed epoch differences in climatological DJF 500-hPa winds (mph) for the recent period (1995–2001) minus the earlier period (1967–93) from the ERA5 reanalysis; stronger winds in the more recent period are indicated by red colors, and weaker winds during the more recent period are indicated by darker blue colors. (b) As in (a), but for 700 hPa. The black dot at 40°N is Boulder; high-altitude topography that extends above 700 hPa is indicated by gray shading. The ERA5 data have 0.25° resolution so the representation of topography (thin contours) is necessarily smoothed. See Fig. 7d for a more accurate depiction of topography showing the Continental Divide as a continuous barrier stretching from northern to southern Colorado.

In terms of a possible connection to anthropogenic climate change, we compare epoch differences of DJF 500-hPa total wind speeds from the ERA5 reanalyses (Fig. 16a), with future (2081–2100) minus historical (1991–2010) 500-hPa total wind speeds from the CESM2 large-ensemble (LE) simulations in Fig. 16b [Rodgers et al. 2021; increasing greenhouse gases following shared socioeconomic pathway (SSP) 3–7.0, 10 ensemble members]. Both the observations for recent changes and model simulations for future changes show mean increases of total wind speed near 500 hPa over Boulder (differences of about +2 mph and standard deviations of roughly 5 mph for observations; differences of about +3 mph and standard deviations of around 1 mph from the much larger number of samples from the CESM2 LE). This is consistent with the increase in vertical wind shear above Boulder noted earlier for zonal winds (Figs. 14 and 15b).

At these larger spatial scales, there are greater increases of 500-hPa total wind speed to the south of Boulder and decreases to the north in both observations and model simulations. To provide insight into these changes, Woolings et al. (2023) show trends in zonal mean *u*-component winds and temperatures from ERA5 for DJF for 1979–2019 (their Fig. 1). Essentially, the increase in midtropospheric temperatures in the tropics and subtropics from greater convection and latent heat release increases the meridional temperature gradient in the midtroposphere and contributes to a northward shift and strengthening of the westerlies from about 30° to 45°N. Meanwhile, the enhanced high latitude warming north of 60°N reduces the meridional temperature gradient throughout the troposphere near about 40°–70°N contributing to the weakening of zonal mean winds at 500 hPa north of about 45°N. These global zonal-mean changes are reflected in our regional plot in Fig. 16a where 500-hPa winds strengthen south of about 42°N and weaken north of about 42°N. These changes show up both in the trends in Woolings et al. (2023) and our regional epoch difference plots and are likely relevant to the background base state that sets the stage for a reduction of strong wind events near Boulder.

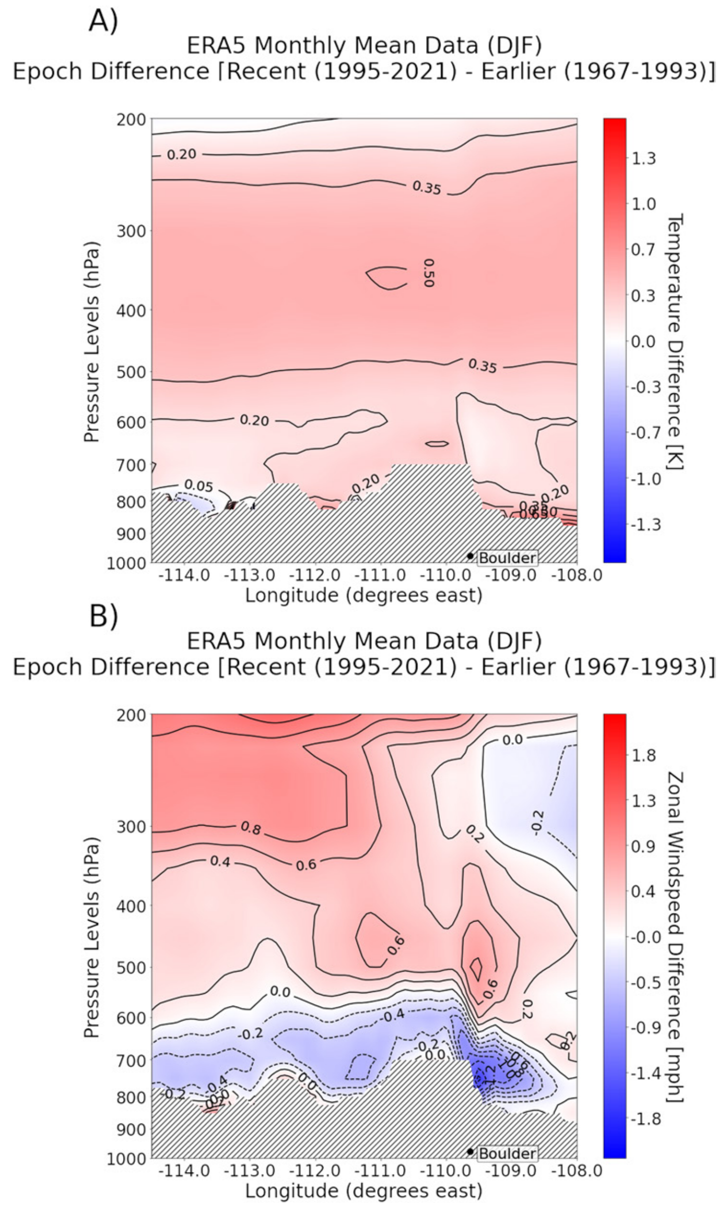

Fig. 15. Epoch differences for mean DJF climatologies for the recent period (1995–2021) minus the earlier period (1967–93) from the ERA5 reanalysis for (a) vertical cross section of temperature (°C) at the latitude of Boulder (40°N) from (left) western Colorado to (right) east of Boulder; (b) as in (a), but for zonal winds (mph); black hatching indicates low-resolution topography in the reanalysis.

Future climate changes in the model are mainly due to increasing human-produced greenhouse gases, and the pattern of those future changes (Fig. 16b) resembles the pattern of the more recent changes (Fig. 16a). This is suggestive of a possible role for human-caused climate change in the reductions in peak gusts that have been observed in and around Boulder as well as increased midtropospheric wind speeds over Colorado. As noted earlier, this possibility will be explored more quantitatively in the planned WRF simulations.

4. Conclusions

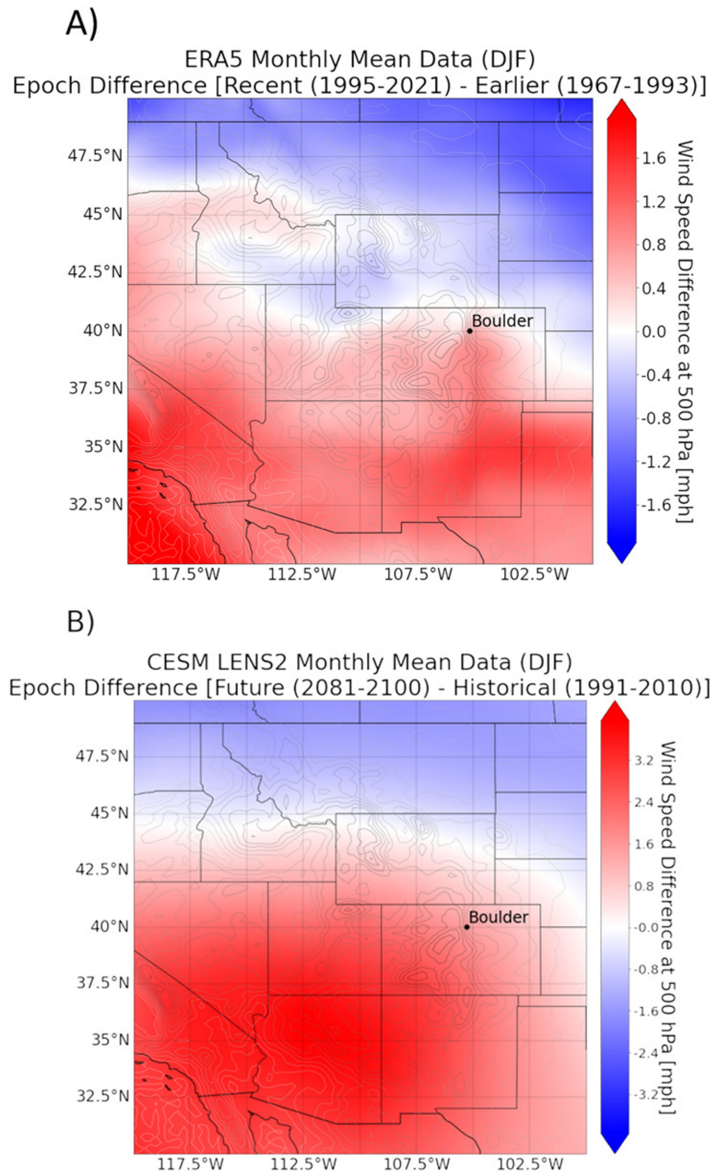

Fig. 16. Epoch differences for mean DJF climate for the recent period (1995–2021) minus the earlier period (1967–93) from the ERA5 reanalysis for 500-hPa total wind speed (mph; also shown for a smaller domain in Fig. 14a); (b) as in (a), but for future minus present total wind speed differences (mph) based on a composite mean of CESM2-LE members during the late twenty-first century (2081–2100) and the historical period (1991–2010). Thin contours are the ERA5 0.25° resolution topography. Note different color scales in the two panels chosen to highlight the similarities in the patterns of the anomalies; the magnitudes for the end of the twentieth century are about twice the historical since the forced response at the end of the twenty-first century is much greater than the historical period.

The epic extreme downslope windstorms that hit Boulder in the 1960s, 70s, and 80s, documented by anemometer measurements made on the roof of the NSF NCAR Mesa Laboratory, seem to have become less severe after the 1990s. We examine the various factors that could have produced either the perception of reduced wind impacts or an actual weakening of extreme downslope winds. The apparent decrease of peak gusts during severe downslope windstorms measured at NSF NCAR is likely real, as indicated by measurements from sonic anemometer instruments in two locations on the Mesa Laboratory roof in the 2020s compared to earlier propeller anemometer measurements prior to 1996, NOAA Storm Reports from three counties along the Front Range (including Boulder County) that suggest a secular decrease in strong wind gusts, and the ERA5 reanalyses that show a large-scale decrease in lower-tropospheric winds in the lee of the Rockies below about 600 hPa in the more recent period. The tightening of building codes in Boulder to equip structures to resist wind damage has undoubtedly contributed to the reduction of damage from windstorms. The increase of roughness length from tree growth in Boulder over the decades also likely contributed to somewhat reduced winds at the surface. Pine trees near the Mesa Laboratory have also grown taller but are still well below the height of the anemometers on the roof. In terms of changes in mean climate, we show that the midtroposphere has warmed over this time period along with a strengthening of mean winds above 500 hPa and a weakening of mean winds near 700 hPa near Boulder, thus increasing vertical wind shear. This is consistent with a long-term trend for an increase in observed mean vertical wind shear in the zonal mean from 35° to 50°N that has been noted previously (Woolings et al. 2023).

In terms of quantifying what is causing these changes in Boulder's winds, a study is underway to run the WRF Model for historical case studies of strong downslope wind events in Boulder to contrast the effects of historical and future forcings, the latter from the CMIP6 models. This study will address how these changes in mean climate may affect the characteristics of severe downslope wind events, examine other data sources such as CONUS404, and provide prospects for the future of such events.

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Data availability statement. The fifth major global reanalysis produced by ECMWF (ERA5) datasets can be found on ECMWF website, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5, also available at https://confluence.ecmwf.int/display/CKB/Use+Case+2%3A+ERA5+hourly+data+on+single+levels+from+1940+to+present?desktop=true&macroName=page-info, and also from the NSF NCAR Research Data Archive, ds633.0, https://doi.org/10.5065/BH6N-5N20 [ERA5 reanalysis (0.25 degree latitude–longitude grid)], ds633.5, https://doi.org/10.5065/JAXB-X906 [ERA5 monthly mean back extension 1950–78 (preliminary version)], and ds633.1, https://doi.org/10.5065/P8GT-0R61 [ERA5 reanalysis (monthly mean 0.25 degree latitude–longitude grid)]. National Weather Service Storm Reports can be found at https://www.ncdc.noaa.gov/stormevents/, and the curated wind record from Catherine Smith at NOAA PSL, University of Colorado Cooperative Institute for Research in the Environmental Sciences (CIRES), can be found at https://psl.noaa.gov/boulder/wind.html. Quality controlled NSF NCAR anemometer data can be accessed at https://zenodo.org/records/14171096. CESM2-LENS datasets can be found on the NSF NCAR website at https://www.cesm.ucar.edu/community-projects/lens2/data-sets.

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